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VII. *On the Moving Coil Ballistic Galvanometer.* By R. Ll. Jones, *M.A., The Presidency College, Madras.*

Received November 3, 1913.

1. In the theory of the moving coil ballistic galvanometer as usually presented, the motion of the coil is assumed to be oscillatory. But when a search coil of low resistance, such as is employed to explore magnetic fields, is connected to the galvanometer, the motion may become aperiodic. The theory as usually given in text-books is not directly applicable to this case. To evade this difficulty the suggestion is sometimes made to insert sufficient resistance in the circuit to make the motion oscillatory. This is unnecessary, for, as the following considerations show, the throw of the galvanometer is proportional to the change in flux, even when the motion is dead-beat, provided the change is quickly effected. As it is far quicker and much more convenient to work with a galvanometer when its motion is aperiodic than when it is oscillatory, the matter is of some practical importance, and the treatment given below may not be without interest.

In the Grassot fluxmeter, with its very weak torsional control, the throw is proportional to the change in flux, and is, within limits, independent of the time taken to effect the change. On the other hand, in an ordinary galvanometer, with its stronger control, the throw will be very small when the rate of change is the slowest permissible with the fluxmeter, and will have a much greater (its maximum) value when the change is instantaneous. Further, we would naturally expect, even when the change is instantaneous, the throw to be greater when the torsional control is weak than when it is strong. This inference is confirmed by the investigation given below.

In this Paper the aperiodic motion of the moving coil galvanometer is first considered ; then an account of some observations with a galvanometer is given which confirm some deductions from the theory ; and finally the results obtained are applied to determine the exact relation between its throw and the change in the flux through the search coil which produced it.

2. The coil of the galvanometer turns about a vertical axis in the plane of the coil, passing through its centre of gravity and perpendicular to the field. In the position of

rest the normal to the plane of the coil is at right angles to the lines of force, and the number of lines passing through it is zero. The deflection θ of the coil is conveniently measured by the angle this normal makes with its direction in the position of rest. Let A be the effective area of the coil and H the strength of the field. Then N, the number of lines passing through the coil in the position θ, is given by

$$N=AH \sin \theta.$$

The E.M.F. induced in the galvanometer coil in this position by its motion is $-A \cdot H \cos \theta \cdot \dot{\theta}$. This is equal to $-AH \cdot \dot{\theta}$, since θ is always small in practice. Let i be the current in the coil at this instant. Then

$$i=-\frac{AH}{R} \cdot \dot{\theta}-\frac{L}{R} \cdot \frac{di}{dt},$$

where R is the total resistance of the galvanometer and the search coil in series with it. Since the movement is slow, we can neglect the second term and thus obtain

$$i=-\frac{AH}{R} \cdot \dot{\theta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The couple acting on the moving system tending to increase θ, due to this current, is $-\frac{A^2H^2}{R} \cdot \theta$, where again we assume θ small and write $\cos \theta=1$.

The equation of motion of the coil is

$$\ddot{\theta}+\frac{A^2H^2}{IR} \cdot \dot{\theta}+\frac{c}{I} \cdot \theta=0,$$

where I is the moment of inertia of the coil about its axis of rotation and c is the torsional control of the suspending strip.

This equation may be written

$$\ddot{\theta}+2\lambda\dot{\theta}+n^2\theta=0. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Its solution is

$$\theta=e^{-\lambda t}(Ae^{pt}+Be^{-pt}), \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where $p=(\lambda^2-n^2)^{\frac{1}{2}}$.

3. Let an angular velocity, ω, be given to the coil in its position of rest. Then we have

$$\left.\begin{aligned}\theta&=0\\ \dot{\theta}&=\omega\end{aligned}\right\} \text{at the time } t=0.$$

Substituting these values in (3) and its first derivative, we get

$$A=-B=\frac{\omega}{2p}.$$

The position and the velocity at any time t are thus given by

$$\theta=\frac{\omega}{2p}e^{-\lambda t}(e^{pt}-e^{-pt})=\frac{\omega}{2p}.P, \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$\dot{\theta}=\frac{\omega}{2p}e^{-\lambda t}\{-(\lambda-p)e^{pt}+(\lambda+p)e^{-pt}\}. \quad . \quad . \quad . \quad (5)$$

From (5) we deduce that $\dot{\theta}=0$ and therefore θ will be a maximum at the time t_1 where

$$t_1=\log_e\left(\frac{\lambda+p}{\lambda-p}\right)^{1/2p}.$$

The maximum value of θ is θ_0 where

$$\theta_0=\frac{\omega}{n}.\left(\frac{\lambda-p}{\lambda+p}\right)^{\lambda/2p}.$$

The ratio of the second term on the right-hand side of (4) to the first is e^{-2pt}. This becomes smaller and smaller as t increases. Hence, after a certain time, the position of the coil will be given with sufficient accuracy by

$$\theta=\frac{\omega}{2p}e^{-(\lambda-p)t}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

4. To test relation (6) observations were made on a galvanometer (N.B. No. 30,532), the moving coil of which was wound on a narrow non-conducting frame, and had a resistance of about 800 ohms. The suspension was phosphor-bronze strip, and the field was approximately uniform. The period of oscillation on open circuit was 12·32 seconds. The air damping was small, and its effect has been left out of account throughout. The observations showed that when the galvanometer was deflected and the circuit then closed through a small resistance the time the deflection took to fall to half its value was always the same and was independent of t (provided the deflection was not observed too near the turning point). In other words, if θ, the deflection, be a function of t, say $f(t)$, the value of $f(t+\tau)$, where τ is a certain interval, was always equal to $\frac{1}{2}f(t)$, no matter what the value of t be. This shows that $f(t)$ must be a simple exponential function of the

time, of the form $Ae^{-\kappa t}$, where $e^{-\kappa\tau}=\frac{1}{2}$. The observations confirm the form of relation (6).

5. Since $$\theta=\frac{\omega}{2p}\cdot e^{-(\lambda-p)t},$$

when t exceeds a certain value, and

$$\frac{\theta}{2}=\frac{\omega}{2p}e^{-(\lambda-p)(t+\tau)},$$

we have, by combining the two, $\lambda-p=\dfrac{\log_e 2}{\tau}$.

Expanding p in powers of n^2/λ^2, and neglecting all terms after the second, we get

$$\tfrac{1}{2}\frac{n^2}{\lambda}=\frac{0{\cdot}6931}{\tau}$$

or $$R\tau=\frac{A^2H^2}{I}\cdot\frac{0{\cdot}6931}{n^2}=\text{constant}. \quad . \quad . \quad . \quad . \quad (7)$$

To test this relation, observations were made with the galvanometer mentioned in § 4. The values of τ observed with different external resistances are given in the second column of the following table ; the third column gives the product $R\tau$.

R = 800 +	τ.	$R\tau$ (approx.).
0 ohms	17·60 seconds	14,100
100 „	15·77 „	14,200
200 „	14·47 „	14,500
300 „	12·78 „	14,100
400 „	11·47 „	13,800
500 „	10·57 „	13,700
600 „	10·00 „	14,000

The results given in the above table are, on the whole, in fair agreement with the deduction expressed in (7). When the external resistance is more than 600 ohms, relation (7) is no longer sufficiently accurate ; higher powers of n^2/λ^2 must in that case be retained in the expansion of p.

6. To illustrate the results obtained in § 3, consider the case of the galvanometer described in § 4, when the outside resistance is negligible. Since its period on open circuit is 12·32 seconds, this gives us $n^2=0{\cdot}2601$, and (7) becomes

$$R\tau=2{\cdot}665\cdot\frac{A^2H^2}{I}. \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Since R = 800 ohms and $\tau=17{\cdot}60$ seconds, we get from (8)

$\lambda=3{\cdot}302$ and $p=3{\cdot}262$. Substituting these values in the expression for t_1 in § 3, we get

$$t_1=0{\cdot}782 \text{ second.}$$

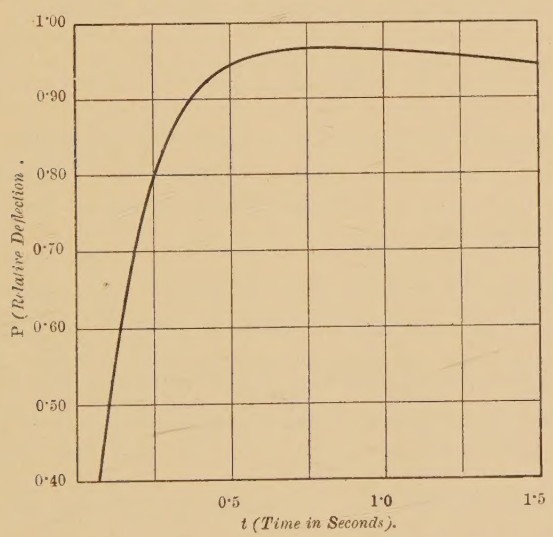
The coil always comes to rest in this time, 0·782 second, whatever be the angular impulse given to it. The throw is given by

$$\theta_0=0{\cdot}148\times\omega.$$

The following table gives the value of P, the variable part of the expression for θ in (4) for different values of t:—

t.	P.	t.	P.	t.	P.
0·1 sec.	0·487	0·6 sec.	0·957	1·5 sec.	0·942
0·2 ,,	0·723	0·7 ,,	0·962	2·0 ,,	0·923
0·3 ,,	0·848	0·8 ,,	0·963	5·0 ,,	0·819
0·4 ,,	0·912	0·9 ,,	0·962	10·0 ,,	0·670
0·5 ,,	0·943	1·0 ,,	0·960	...	...

The values are plotted in the accompanying diagram. They show that the galvanometer coil moves comparatively rapidly



to its maximum deflection and then slowly returns towards its position of equilibrium ; this is in accordance with observation.

7. Let the flux through the search coil change, and let $E=\frac{dN_2}{dt}$

denote the E.M.F. induced in it. Then we have, as in the theory of the fluxmeter,

$$Ri+AH\,.\,\dot{\theta}+L\frac{di}{dt}=E$$

for the current and

$$I\ddot{\theta}-AHi+c\theta=0$$

for the motion of the galvanometer coil.

Substituting for i in the second equation the value obtained from the first and integrating between the limits $t=0$, the time when the flux begins to change, and $t=t_1$, the time when the galvanometer comes to rest at its maximum deflection, we get

$$[I\dot{\theta}]_0^{t_1}=\left[-c\int\theta dt+\frac{AH}{R}\left(\int Edt-AH\,.\,\theta-Li\right)\right]_0^{t_1}.$$

Now, $\dot{\theta}=0$ and $i=0$ at times $t=0$ and $t=t_1$, while $\theta=0$ at time $t=0$ and $\theta=\theta_0$ at time $t=t_1$. Remembering that $\int_0^{t_1}Edt=N_2$, the total change in flux through the coil, we get

$$N_2=AH\,.\,\theta_0+\frac{Rc}{AH}\int_0^{t_1}\theta dt. \quad . \quad . \quad . \quad . \quad . \quad (9)$$

In the fluxmeter the factor c is so small that the second term on the right-hand side of (9) is negligible compared with the first. In the ordinary moving-coil galvanometer this is not necessarily the case.

The ratio of the second term to the first is $\frac{\int_0^{t_1}\theta dt}{\theta_0}\cdot\frac{Rc}{A^2H^2}$. If this ratio be constant and independent of N_2, then N_2 will be proportional to θ_0. The factor $\frac{Rc}{A^2H^2}$ depends on the galvanometer and the resistance of the search coil, and is evidently constant with a given search coil. To find the value of $\frac{\int_0^{t_1}\theta dt}{\theta_0}$ we will assume that the change in flux (N_2) has been completely effected before the galvanometer coil has appreciably moved from its position of rest. The effect of this will be to give an angular impulse to the coil; its subsequent motion will then be given by (4). The value of $\int_0^{t_1}\theta dt$ will

depend only on λ, p and ω, and can be determined from (4), while θ_0 also depends on λ, p and ω alone. The ratio $\frac{\int_0^{t_1}\theta dt}{\theta_0}$ depends on λ and p, and does not involve ω.

Hence the ratio is independent of N_2, and if the flux change be sudden *the throw will be proportional to* N_2.

8. The ratio of the two terms in (9) is readily evaluated in any given case. With the galvanometer used for the observations recorded in §§ 4-5 and a search coil of negligible resistance, the value of $\frac{Rc}{A^2H^2}\left(=\frac{n^2}{2\lambda}\right)$ is 0·039. The value of $\int_0^{t_1}\theta dt$ is most easily obtained from the results given in § 6. These give for $\int_0^{t}\theta dt$ the value 0·63 θ_0. Thus the ratio is 0·024. Hence, with the given galvanometer and a search coil of negligible resistance, the throws are about $2\frac{1}{2}$ per cent. less than they would be with an infinitely weak control.

ABSTRACT.

The author first considers the mathematical theory of a moving coil galvanometer in which the damping is such as to make the motion non-oscillatory; then an account is given of some observations on a galvanometer which confirm some of the deductions from the theory, and the results obtained are applied to find the relation between the galvanometer throw and the change of flux in the search coil which produces it.

DISCUSSION.

Prof. C. H. Lees thought it likely that with a highly damped galvanometer the creeping at the end would create a difficulty as to what reading to take.

Prof. T. Mather stated that the creep presented no difficulty, since it was easy to get the maximum deflection reached. The real difficulty was in getting the true zero.

Mr. A. Campbell mentioned that although the case of the strongly damped galvanometer when used with a search coil did not appear to be treated in any English text-book, he had found it described in Kohlrausch's "Lehrbuch der praktischen Physik" (10th edition, 1905).

VIII. *A Note on Aberration in a Dispersive Medium and Airy's Experiment.* *By* JAMES WALKER, *M.A.*

In a Paper entitled "Aberration in a Dispersive Medium"* Lord Rayleigh accepts the view of Ehrenfest† that in the case of aberration we have to deal with a peculiarity impressed on a wave-front and that in consequence the angle of aberration is v/U, v being the velocity of the earth in its orbit and U the group velocity, instead of v/V, where V is the wave velocity. This being so, it becomes necessary to consider Airy's experiment, in which he found the same angle of aberration with a telescope filled with water as with one that contained air.

In his explanation of this experiment Lord Rayleigh replaces the telescope by two perforated screens moving together with the velocity of the earth, the space between being occupied by water at rest relatively to the screens, and calculates the angle through which the hole in the hinder screen must be displaced, in order that light from a star falling normally on the foremost screen may pass through the system.‡

If in this explanation we make the changes rendered necessary by the view that it is the group-velocity with which we are concerned, we find that the angle of aberration is $\mu^{-2}v/U$ measured in water, corresponding to an angle $\mu^{-1}v/U$ measured in air.

The same result may be obtained from an analytical solution. Let us take the anterior screen as the plane of xy, the axis of x being drawn in the direction of its motion, and let the centre of the hole of width $2d$ be at $x=0$ at time $t=0$. Then at the point x just behind the screen the luminous disturbance will commence at time $(x-d)/v$ and end at time $(x+d)/v$.

Now
$$\frac{2}{\pi}\int_0^\infty \frac{\sin \alpha}{\alpha} \cos \frac{vt-x}{d}\alpha d\alpha \quad . \quad . \quad . \quad . \quad . \quad (1)$$
has the value unity when t lies between $(x-d)/v$ and $(x+d)/v$

* "Phil. Mag. (6), XXII., 130 (1911).

† "Ann. d. Physik.," (4), XXXIII., 1571 (1910).

‡ "Nature," XLV., 499 (1892). "In consequence of the movement of the water the wave after traversing the first aperture is carried laterally with the velocity $v(1-\mu^{-2})$ and this is to be subtracted from the actual velocity v of the aperture in the posterior screen. The difference is $\mu^{-2}v$. The ratio of this to the velocity of light in water (V/μ) gives the angular displacement of the second aperture necessary to compensate for the motion. We thus obtain $\mu^{-1}v/V$. This angle being measured in water corresponds to v/V in air, so that the result of the motion is to make the star appear as if it were in advance of its real place by the angle v/V precisely as would have happened had the telescope contained air or vacuum instead of water."

and is zero when t is without these limits. If, then, $\cos nt$ represents the vibration incident on the screen, the vibration just behind it will be

$$\frac{2}{\pi}\cos nt\int_0^\infty \frac{\sin\alpha}{\alpha}\cos\frac{\alpha}{d}(vt-x)d\alpha, \quad . \quad . \quad . \quad (2)$$

which represents an aggregate of terms such as

$$a\cos m(vt-x)\cos nt, \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which mv will be small compared with n, for $\sin\alpha/\alpha$ becomes insensible long before $\alpha v/d$ becomes comparable with n, provided d is not very small.

The expression (3) is the vibration just behind the screen considered by Lord Rayleigh in the Paper above cited in the case of a stagnant dispersive medium. Taking as the vibration at a finite distance from the screen

$$\varphi=\tfrac{1}{2}a\cos\{(n+mv)t-mx-k_1z\}+\tfrac{1}{2}a\cos\{(n-mv)t+mx-k_2z\}, \quad (4)$$

where k_1, k_2 are determined so as to satisfy in each case the general differential equation of propagation,

$$\frac{\partial^2\varphi}{\partial t^2}=V^2\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial z^2}\right). \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

in which, the medium being dispersive, V must be given values V_1, V_2 when the coefficient of t is $n+mv$ or $n-mv$, he shows that the angle of aberration due to v is

$$-\frac{x}{z}=\frac{k_1-k_2}{2m}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

In the case of a medium moving with speed v in the direction of x, we have instead of (5)

$$\frac{\partial^2\varphi}{\partial t^2}+2v(1-\mu^{-2})\frac{\partial^2\varphi}{\partial t\partial x}=V^2\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial z^2}\right),$$

in which suffixes (1) or (2) are to be assigned to V and μ when the coefficient of t is $n+mv$ or $n-mv$. Thus

$$V_1^2(m^2+k_1^2)=(n+mv)^2-2mv(1-\mu_1^{-2})(n+mv)\doteq(n+\mu_1^{-2}mv)^2,$$

$$V_2^2(m^2+k_2^2)=(n-mv)^2+2mv(1-\mu_2^{-2})(n-mv)\doteq(n-\mu_2^{-2}mv)^2,$$

whence the difference k_1-k_2 may be regarded as corresponding

* k has been substituted for μ in the above, so as to retain μ for representing the refractive index.

to a change in the coefficient of t from $n+\mu_1^{-2}mv$ to $n-\mu_2^{-2}mv$, the medium being at rest. Hence, denoting the general coefficient of t by σ, of which k is a function,

$$k_1-k_2=(\mu_1^{-2}+\mu_2^{-2})mv\frac{dk}{d\sigma}\doteq 2\mu^{-2}mv\frac{dk}{d\sigma}=\frac{2\mu^{-2}mv}{\mathrm{U}};$$

and accordingly

$$-\frac{x}{z}=\mu^{-2}\frac{v}{\mathrm{U}}$$

represents the angle of aberration in the medium, to which corresponds the angle $\mu^{-1}v/\mathrm{U}$ measured in air.

Taking $\quad \mathrm{V}=\mathrm{V}_0(\mathrm{A}+\mathrm{B}k^2)=\mathrm{V}_0\left\{\mathrm{A}+4\pi^2\mathrm{B}\left(\frac{\mu'}{\lambda}\right)^2\right\}$,

where λ represents the wave-length *in vacuo*, we have

$$\mathrm{U}=\frac{d(k\mathrm{V})}{dk}=\mathrm{V}\left\{1+4\pi^2\mathrm{B}\,.\,2\mu\,.\left(\frac{\mu}{\lambda}\right)^2\right\},$$

and calculating B from the data for

$\lambda=6{\cdot}562\times10^{-5}$, $\mu=1{\cdot}3312$, and for $\lambda=4{\cdot}311\times10^{-5}$, $\mu=1{\cdot}3406$,

we find $\quad 4\pi^2\mathrm{B}=-9{\cdot}47\times10^{-12}$,

whence for sodium light ($\lambda=5{\cdot}893\times10^{-5}$, $\mu=1{\cdot}3331$)

$$\mathrm{U}=\mathrm{V}(1-0{\cdot}0129) \text{ or } \mathrm{V}/\mathrm{U}=1{\cdot}013,$$

so that the angle of aberration is increased by about 1 per cent.

Considering the difficulties of Airy's experiment, it seems very unlikely that so small a variation as this could be detected, and, in fact, there appears to be an uncertainty of about this amount in the determination of the angle of aberration under ordinary circumstances.

ABSTRACT.

The view recently adopted by Lord Rayleigh that in the case of aberration we are concerned with the group-velocity instead of with the wave-velocity, makes it necessary to consider the experiment of Airy, in which he measured the angle of aberration with a telescope filled with water.

A modification of Lord Rayleigh's explanation of this experiment leads to the result that the angle of aberration thus determined corresponds to an angle $\mu^{-1}v/\mathrm{U}$ measured in air. The same result is obtained from an analytical investigation, and a numerical calculation shows that the increase in the angle is about 1 per cent.—an amount that is probably too small to be detected.

IX. *The Thermal Expansions of Mercury and Fused Silica.*

By F. J. HARLOW, *A.R.C.S., B.Sc., Assistant Lecturer in Physics, Sir John Cass Technical Institute.*

RECEIVED NOVEMBER 11, 1913.

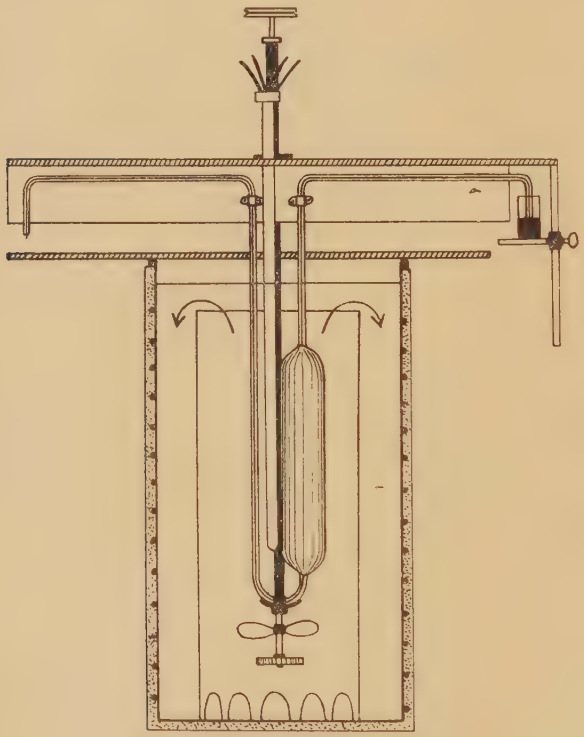
Introductory.—In a previous communication on the subject of the cubical expansion of fused silica* an account was given of observations which had been made on the apparent coefficient of expansion of mercury in fused silica by the weight thermometer method ; these observations were restricted to the temperatures of 0°C., 100°C. and 184°C. In view of the importance of establishing the correct values of the absolute coefficient of expansion of mercury and silica, it was thought that the extension of these observations to other temperatures would be useful. The results given in the following Paper were obtained with two of the cylindrical weight thermometers previously used, and comprise readings at frequent intervals from 0°C. to 300°C. The apparent coefficients for the temperature ranges 0°C. to 100°C., and 0°C. to 184°C. are in good agreement with the previous determinations, although an entirely different method of heating was adopted.

At the suggestion of Prof. Callendar, to whom I am indebted for guidance in this work, a spherical bulb was also used, as the earlier observations appeared to indicate that one could not assume the silica to be isotropic ; and if this were the case one would scarcely expect to get the same value for the apparent coefficient of expansion of mercury as with the cylindrical bulbs. The nature of the spherical bulb, however, which was not constructed specially for the experiment, did not allow of a continuous set of observations being made conveniently, so that results for the fundamental interval only were obtained. These, as will be seen, did not differ by more than 1 part in 18,000 from similar observations with the cylindrical bulbs, so that, in so far as this experiment has weight, the cubical coefficient of expansion may be considered, for these bulbs at any rate, to be three times the linear. One has thus felt

* The Cubical Expansion of Fused Silica, &c., " Proc." Phys. Soc., December, 1911.

justified in including in this Paper values of the coefficients of absolute expansion of mercury deduced from the observations of the apparent coefficients.

The Heating Bath.—In order that observations might be made at any desired temperature, the method of heating the bulbs by means of an electrically-heated oil bath was adopted. The arrangement is shown in the accompanying figure. A



Weight Thermometer in Heating Bath.

cylindrical copper vessel 30 cm. by 15 cm. was covered with asbestos paper, and around this were wound two coils of Eureka wire in parallel, the whole being lagged with asbestos cloth. Inside this vessel was fixed a concentric cylinder extending from the bottom to within about 5 cm. of the top. This was slotted at its base so as to allow a free circulation of the oil. The bulb of mercury, the filling of which under a

vacuum has been fully described in the earlier Paper already referred to, was suspended at the centre of the cylinder by a hollow steel rod carrying a support for it at its lower end. The bulb stems were held as shown by a wooden cross-piece, also attached to the hollow steel rod. This cross-piece carried in addition a mercury thermometer for measuring the temperature of the exposed stems, and at its end a small adjustable platform to carry the overflow vessel. The advantage of using a hollow steel rod was, first, that the conduction of heat along it from the bath was small; and, secondly, that it served to carry a narrow rod for driving the stirrer. The stirrer, which was of the screw type, was driven by gear wheels almost vertically beneath the bulb. The oil was thus caused to circulate rapidly round the bulb, and at the same time a continuous flow was maintained up the central cylinder and down past the heated surface of the outer, as indicated by the arrows. The bath was closed at the top with sheets of uralite suitably cut for the supporting rod, bulb stems, and thermometer to pass through. These sheets extended outwards as far as possible in order to diminish the heating of the exposed stems by convection from the sides of the vessel.

The Observations.—The temperature of the oil bath was recorded by a platinum thermometer of about 5 ohms fundamental interval placed in the bath with its coil alongside the silica bulb. The temperature could be read by means of the bridge and galvanometer used to 1/500th of a degree at the lower temperatures and with proportionate accuracy at the higher. When the conditions were favourable, by a careful adjustment of the heating current the bath could be maintained to within 1/100th of a degree or so of any desired temperature for several minutes. The length of time usually allowed for a reading, the first at the particular temperature, was about an hour. The heating-up was performed as rapidly as possible, and then, when the conditions had become more or less steady, the temperature was kept within about a tenth of a degree of the desired temperature for some considerable time. When it was thought that the mercury in the bulb had attained the temperature of the bath, the final careful adjustment was made. It was frequently possible to keep the spot of light dead steady for a minute or two. If the temperature had not varied appreciably for several minutes the overflow vessel was removed and weighed. The temperature of the bath was then allowed to fall slightly to prevent loss of mercury

by a possible rise of temperature. A second reading was often taken as a check, and for this a quarter of an hour or so was found to be sufficient for the conditions to have become steady again.

The fact that there was good agreement between the readings when the desired temperature was approached, sometimes from above and sometimes from below, showed that there was no error due to a temperature lag of the mercury behind that of the bath. In order to test the efficiency of the stirring, readings were also taken with the direction of flow of the oil reversed. No systematic changes in the readings could be detected, which proves that the stirring arrangement was entirely satisfactory.

The readings above 100 deg. were made with a heavy lubricating oil, which was sufficiently fluid at the higher temperatures to allow of a vigorous stirring: for those at and below 100 deg. paraffin oil was found to be more suitable.

Ice readings were taken at frequent intervals during the course of the experiments. After being allowed to cool down to atmospheric temperature, the bulb and its attachments were withdrawn and cleaned, and then suspended in a glass cylinder which was subsequently packed with ice shavings. The vessel was provided with an outlet at its base, so that any excess water could be drained away. The constancy of the ice readings, even after heating to 300 deg., proved the absence of thermal hysteresis, thus bearing out the statements made in the previous Paper concerning the suitability of silica as the envelope for a thermometer.

The larger of the two cylindrical bulbs used was the only one suitable for observations at the lower temperatures on account of the smallness of the stem exposure correction, which, for the small bulb, formed an appreciable fraction of the overflow, the tubes of this being, unfortunately, somewhat wider than those of the large bulb.

The observations on the fundamental interval with the spherical bulb were made with ice and steam in the usual manner, this bulb, as has already been mentioned, not being suitable for observations with the oil bath.

The Apparent Coefficients of Expansion of Mercury in Silica.—A summary of the readings and calculated apparent coefficients is given in Tables I., II. and III. for the three bulbs; Table IV. contains the collected results.

TABLE I.—*Large Cylindrical Bulb.*

Mass of mercury filling to mark at 0°C. 1,912·70 gms.

Temp. °C.	Date.	Stem correction in gms.	Corrected overflow in gms.	Apparent coeff. $\times 10^8$.
	1913.			
29·993	January 24th	0·0003	10·3048	...
	April 1st	0·0003	10·3022	...
	April 4th	0·0003	10·3042	...
	April 4th	0·0003	10·3035	...
	April 11th.....	0·0003	10·3063	...
			10·3042	18,060
49·993	February 28th	0·0007	17·1226	...
	February 28th	0·0007	17·1246	...
	March 18th	0·0007	17·1202	...
	March 28th	0·0008	17·1209	...
	April 4th	0·0006	17·1242	...
			17·1225	18,068
74·993	February 21st	0·0013	25·5894	...
	February 28th	0·0012	25·5883	...
	March 4th.....	0·0014	25·5877	...
	March 18th	0·0013	25·5891	...
	March 18th	0·0014	25·5883	...
			25·5886	18,081
99·991	January 14th	0·0016	34·0044	...
	February 18th	0·0019	34·0067	...
	March 4th.....	0·0018	34·0047	...
	April 10th.....	0·0020	34·0050	...
	May 26th	0·0026	34·0066	...
			34·0055	18,102
184	May 26th	0·0030	62·0332	...
	May 30th	0·0030	62·0376	...
	May 30th	0·0030	62·0368	...
	June 2nd	0·0028	62·0395	...
			62·0368	18,218
200	May 30th	0·0030	67·3456	...
	June 2nd	0·0030	67·3480	...
			67·3468	18,248
250	May 30th	0·0050	83·9148	...
	June 2nd	0·0052	83·9188	...
			83·9168	18,355
300	May 27th	0·0060	100·5001	...
	May 30th	0·0060	100·5063	...
	June 2nd	0·0061	100·5082	...
			100·5049	18,487

Ice readings :— May 29th ..... 104·8871
May 31st..... 104·8869
June 3rd ..... 104·8876

TABLE II.—*Small Cylindrical Bulb.*

Mass of mercury filling to mark at 0°C. 1,154·66 gms.

Temp. °C.	Date.	Stem correction in gms.	Corrected overflow in gms.	Apparent coeff. $\times 10^8$.
	1912-1913.			
100	November 15th ...	0·0028	20·5268	...
	November 19th ...	0·0028	20·5282	...
	June 30th	0·0050	20·5279	...
	July 4th	0·0050	20·5297	...
	July 10th	0·0042	20·5336	...
			20·5292	18,101
140	July 4th	0·0074	28·6106	...
	July 11th	0·0068	28·6137	...
			28·6122	18,150
184	June 30th	0·0084	37·4525	...
	July 4th	0·0090	37·4528	...
	July 11th	0·0090	37·4550	...
			37·4534	18,220
200	July 4th	0·0096	40·6547	...
	July 11th	0·0110	40·6587	...
			40·6567	18,248
250	June 30th	0·0118	50·6676	...
	July 4th	0·0116	50·6622	...
	July 11th	0·0116	50·6627	...
			50·6642	18,357
300	June 30th	0·0136	60·6746	...
	July 4th	0·0140	60·6849	...
	July 11th	0·0144	60·6879	...
			60·6825	18,490

Ice readings :— June 27th ..... 75·9104
July 3rd ..... 75·9106
July 10th ..... 75·9086
July 16th ..... 75·9090

TABLE III.—*Spherical Bulb.*

Mass of mercury filling to mark at 0°C. 934·66 gms.

Temp. of steam.	Date.	Stem correction in gms.	Corrected overflow in gms.	Apparent coeff. $\times 10^9$.
99·879	June, 1912	0·0018	16·5983	181,017
99·847	,, ...	0·0018	16·5931	181,016
99·815	,, ...	0·0020	16·5861	180,998
100·067	,, ...	0·0018	16·6295	181,022
100·159	,, ...	0·0021	16·6441	181,020
				181,016

TABLE IV.—*Collected Results.*

Temp. range.	Apparent coeff. $\times 10^8$.				
	Large bulb.	Small bulb.	Spherical bulb.	Mean of 1911 observations.	Final mean.
0° to 30°	18,060	...	...	...	18,060
50°	18,068	...	...	...	18,068
75°	18,081	...	...	...	18,081
100°	18,102	18,101	18,102	18,104	18,102
140°	...	18,150	...	...	18,150
184°	18,218	18,220	...	18,221	18,220
200°	18,248	18,248	...	...	18,248
250°	18,355	18,357	...	...	18,356
300°	18,487	18,490	...	...	18,489

Where more results than those quoted were obtained, representative readings are given which have the same average as the larger number of readings. The percentage accuracy is not so great at the lower temperatures as at the higher on account of the smallness of the overflow, but above about 50 deg. the results can be regarded as being accurate to 1 part in 18,000, the accuracy to which one attempted to work throughout. It will be noticed that the readings at the higher temperatures show a gradual increase, not sufficient, however, to affect the results appreciably, This was found to occur invariably when the bulb was heated repeatedly to the higher temperatures, and even for the lower temperatures after continued use. This peculiarity was traced to the expelled mercury carrying back with it a slight amount of contamination, which was most probably either oxide or dissolved gas. It was not sufficient to affect the ice readings appreciably, but caused the subsequent overflows to be larger, particularly those at the higher temperatures. At one time, when the overflows had become much higher than usual after a number of readings had been taken, on putting the bulb under a vacuum at 100 deg. small bubbles of gas appeared around the top part of the bulb. After allowing the mercury to cool down to 0 deg., pumping off this gas and then re-heating while it was still under the vacuum, the normal readings were again obtained. It is probable, therefore, that the lower readings of those quoted are the more accurate, since these were obtained immediately after steps had been taken to remove any trace of contamination either by re-filling or by the method just described. The good agreement obtained between the results with the two bulbs was considered to be a sufficient guarantee of the accuracy of the

observations, especially as the stem exposure correction was so large in the case of the smaller bulb.

The Coefficients of Absolute Expansion of Mercury.—From the above observations on the apparent coefficients of expansion, most of which, as already mentioned, are considered to be accurate to 1 part in 18,000, one could deduce reliable values for the coefficients of absolute expansion of mercury, if the expansion of the silica bulbs were known with certainty. Since the excellent agreement between the results with cylindrical and spherical bulbs seems to warrant the conclusion that the bulbs were isotropic, observations of the linear coefficient alone would be necessary. The Fizeau method appears to be the only one suitable for this purpose, but, unfortunately, the bulbs were too wide for the apparatus at one's disposal.

Mr. A. Eagle, however, has carried out measurements with this apparatus on a narrower tube made by the Silica Syndicate, from whom the bulbs were also obtained. The tube and bulbs will, therefore, most probably have been made in the same way and from similar material, and should, therefore, agree in their thermal expansion. Eagle's values, which have not yet been published, cover the temperature range 0 deg. to 120 deg., and are in excellent agreement with the results obtained by Prof. Callendar by the interference method,* on a rod of silica obtained from the same firm.

Prof. Callendar has kindly furnished me with the equation which represents his results over the range 20°C. to 300°C. This is

$$a_0{}^t = \left\{78{\cdot}0 - \frac{8650}{t+175}\right\} 10^{-8},$$

$a_0{}^t$ being the coefficient of linear expansion between 0°C. and t°C.

The values of $a_0{}^t$ calculated by means of this equation for the various temperatures used in the weight thermometer experiments, and also the deduced values of the coefficient of absolute expansion of mercury, are given in Table V. For comparison, the values obtained from the equations given by Callendar and Moss† and by Chappuis‡ for the absolute expansion of mercury, are also included.

* "The Expansion of Vitreous Silica." "Proc." Phys. Soc. June 15, 1912.

† Phil. "Trans.," January, 1911.

‡ "Procès-Verbeaux." Comm. Int. des Poids et Mesures, 1903.

TABLE V.—*The Absolute Coefficient.*

Temp. range.	Linear coeff. of expansion of silica $\times 10^8$. Callendar.	Absolute coefficients of expansion of mercury $\times 10^8$.		
		Callendar and Harlow.	Callendar and Moss.	Chappuis.
0° to 30°	35·8	18,168	18,095	18,171
50°	39·6	18,188	18,124	18,183
75°	43·4	18,213	18,163	18,211
100°	46·6	18,244	18,205	18,254
140°	50·5	18,305	18,280	...
184°	53·9	18,387	18,371	...
200°	54·9	18,419	18,406	...
250°	57·6	18,537	18,525	...
300°	59·8	18,678	18,657	...

It will be observed that there is a fairly good agreement with Chappuis' values, which were also obtained by the weight thermometer method, but a considerable discrepancy from those of Callendar and Moss obtained by the absolute method; the discrepancy, however, gets less as the temperature rises.

The coefficients of expansion of silica given by Prof. Callendar's equation are rather larger than those obtained by Randall.* If these are used there is quite a good agreement with the results of Callendar and Moss at the higher temperatures.

The large discrepancy which exists between the results of the absolute and weight thermometer methods at the lower temperatures is difficult to explain. It seems that there must be some hitherto undiscovered systematic error in one of the methods, and in view of the importance of a knowledge of the correct thermal expansion of mercury in thermometry of precision, the subject undoubtedly calls for further investigation.

In conclusion, I desire to thank Prof. Callendar for the help and advice he has given me in this work, and the Governors of the Imperial College of Science for permission to work in their laboratories.

ABSTRACT.

A more complete set of observations of the relative coefficients of expansion of mercury in silica than those previously published are obtained by the use of an electrically heated oil bath. The observations comprise readings at frequent intervals up to 300°C., and are in good agreement with the earlier observations, which, when applied to the values of the absolute expansion of mercury given by Callendar and Moss, seemed to show that the cylindrical bulbs used were not isotropic. Further experiments made with a spherical bulb negatived this conclusion. Tables are included in the Paper giving representative observations and the final results. From the values

* "Phys. Rev.," XXX., p. 216, 1910.

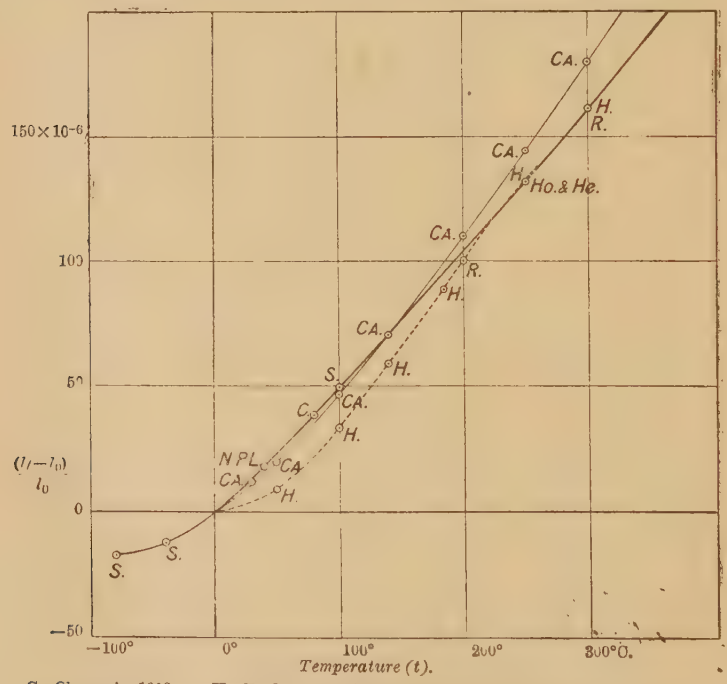
of the coefficients of expansion of silica determined by Prof. Callendar upon specimens similar to those from which the bulbs were made, the coefficients of absolute expansion of mercury are calculated. These over the range of the experiments of Chappuis, who used a similar method, but with bulbs of *verre dur*, are in fair agreement with his results, but differ appreciably from the results of Callendar and Moss obtained by the absolute method. It seems, therefore, that there is some undiscovered fundamental difference in the two methods.

DISCUSSION.

Dr. J. A. Harker said that in Chappuis' experiments bulbs both of platinum-iridium and *verre dur* were used, and no indication was obtained of anomalous expansion of the *verre dur*. This, he thought would have shown up in the expansion of water, as afterwards determined by Chappuis with the same apparatus.

Mr. F. E. Smith believed that despite the agreement between Harlow's results for the coefficient of expansion of mercury with those of Chappuis and others, the results of the hydrostatic method should have precedence. There were always films of moisture on glass and silica which were not removed, even by filling in vacuo, under a temperature of 400°C. This would account for the observed discrepancy, which, as would be expected, disappeared at higher temperatures.

Dr. G. W. C. Kaye exhibited some curves in which were collected the results of various experimenters on the expansion of mercury, including those of Harlow, and indicated the best mean curve obtainable from them.



C. Chappuis, 1903. H. Harlow and Callendar and Moss. Ho. & He. Holborn and Henning, 1908. R. Randall, 1910. S. Scheel, 1907. Ca. Callendar, 1913.

Mr. A. Campbell thought the effect, if any, of surface films of moisture would be evident from results taken with bulbs of different size, since the volume of the film only increased as the square of the dimensions. Mr. Harlow's results appeared to show that the effect was very small.

Mr. Sears called attention to the part played by the late Mr. Donaldson in connection with the discussion on the subject of the coefficients of expansion of fused silica and mercury, and expressed regret that his untimely death had prevented him from carrying out the further experiments which he had intended. Mr. Sears asked leave to re-exhibit two of the lantern slides prepared by Donaldson to illustrate the Paper read by him before the Society in March, 1912, together with a new slide displaying certain of the figures in the subjoined table. In this table, columns 1, 2 and 3 are the same as the columns of Mr. Harlow's Table V., and are reproduced only for convenience of comparison. Column 4 gives the figures which Mr. Harlow would have obtained for the coefficient of expansion of mercury if he had taken for the coefficient of fused silica the values given by Kaye ("Phil. Mag.," October, 1910) as the result of a general survey of the work of all observers up to that date. This was the basis of the formula suggested by Donaldson, and the speaker called attention to the very close agreement between Donaldson's values (column 5) and those actually found by Harlow in the range 0°C.–200°C. Beyond this range Donaldson had not considered it safe to extrapolate with the material then at his disposal, and he had suggested in his Paper the desirability of the experiments which Mr. Harlow had now carried out. Column 6 of the table, as exhibited at the meeting, gave a series of values calculated by the speaker from Harlow's new figures, with the aid of a quartic formula instead of the cubic, to which the paucity of the previous observations had compelled Donaldson to limit himself. This quartic was calculated on the basis of Kaye's value for the coefficient of expansion of silica, partly because this was the basis on which Donaldson worked, and partly because Prof. Callendar's Paper had not been circulated before the meeting, so that the speaker had not known what weight to attach to the formula given in Harlow's Paper. After hearing Prof. Callendar's Paper he was of opinion that the time had now come when, in cases of this kind, the coefficient of expansion of the actual silica vessel used ought to be determined.

Temperature range.	1. Chappuis, 1907.	2. Callendar and Moss, 1911.	3. Harlow, 1913. (Callendar, silica).	4. Harlow, 1913. (Kaye, silica).	5. Donaldson, 1912 (cubic).	6. Sears (Quartic).
0°C.– 30°C.	18,171	18,095	18,168	18,187	18,170	**18,174**
0°C.– 50°C.	18,183	18,124	18,188	18,201	18,192	18,194
0°C.– 75°C.	18,211	18,163	18,213	18,223	18,222	18,221
0°C.–100°C.	18,254	18,205	18,244	18,251	18,254	**18,251**
0°C.–140°C.	...	18,280	18,305	18,305	18,311	18,306
0°C.–184°C.	...	18,371	18,387	18,380	18,380	18,379
0°C.–200°C.	...	18,406	18,419	18,410	18,407	**18,410**
0°C.–250°C.	...	18,525	18,537	18,523	18,497	18,522
0°C.–300°C.	...	18,657	18,678	18,660	18,597	**18,663**
			$\times 10^{-8}$			

Note added since the Meeting.

Column 6 of the table has been revised from that shown at the meeting as follows: On consideration, there appeared still to be some doubt as to

whether it were better to take Kaye's values or Callendar's for the coefficient of expansion of silica when working up Harlow's observations. This for two reasons: In the first place, Callendar and Eagle's experiments, though made with pieces of silica supplied from the same source, were not actually done with the vessels used by Harlow; and, secondly, Callendar's values lie sufficiently near to Kaye's curve to be included amongst the other observations on which that curve was based without seriously distorting it. On the whole, therefore, it seemed fairer to adopt this latter procedure, and the new quartic from which column 6 of the table was calculated was accordingly obtained by using a mean between Callendar's and Kaye's values for silica in working up Harlow's results for mercury. The mean of the figures so obtained and those given by Chappuis was then taken at 0°C. and 100°C. (the two points at which Chappuis' values are most firmly established), and the mean of the Harlow and Callendar-Moss figures at 200°C. and 300°C. (the range of temperature where these two series of results are in reasonably good agreement). The quartic was calculated so as to give the four values thus obtained (distinguished by black type in the table). The formula so obtained seems to represent most fairly the results of all the work done on the subject up to the present. After the remarks which he made at the meeting, Prof. Callendar would presumably agree that, pending some further investigation, the Callendar-Moss values at the lower temperatures must be regarded as being affected by some unexplained source of experimental error.

The formula from which column 6 has finally been calculated is—

$$V = V_0[1 + 10^{-6}\{181{\cdot}456t + 0{\cdot}009{,}205t^2 + 0{\cdot}000{,}006{,}608t^3 + 0{\cdot}000{,}000{,}067{,}320t^4\}].$$

It may be noticed, before leaving the subject, that this formula has the further slight advantage of agreeing better with Chappuis' values over the range −20°C. to 0°C. than did Donaldson's cubic.

Prof. CALLENDAR, in reply, said they had a bulb made with concentric cylinders inside to test for surface film effects. No effect was detected.

X. *Some Characteristic Curves and Sensitiveness Tests of Crystal and Other Detectors.* *By* PHILIP R. COURSEY, *B.Sc., Assistant in the Electrical Engineering Laboratory, University College, London.*

RECEIVED NOVEMBER 25, 1913.

ALTHOUGH much work has been done on the comparative sensitiveness of various types of radio-telegraphic detectors, many questions still remain unsettled.* It has been known for some time in the case of the oscillation valve detectors invented by Dr. J. A. Fleming that if the second differential of the characteristic, or volt-ampere curve, is plotted it bears a considerable resemblance to the curve of sensitiveness of the valve to wireless signals.†

The tests described below were undertaken with a view to finding out whether any similar relation could be traced in other detectors than the valve, such as the crystal receivers so commonly employed in the wireless stations of to-day.

The detectors examined in this manner were ; Carborundum, electrolytic, galena, molybdenite, " perikon " (zincite-chalcopyrite), tellurium-aluminium, and zincite-bornite, while curves were also obtained for the Fleming valves, both carbon and metal filament, and partial tests made on carbon-steel, chalcopyrite, bornite, zincite, silicon, tellurium-zincite, and other detectors, but complete curves for the latter were not obtained, in many cases on account of their relative insensibility. The Marconi magnetic detector, belonging to a different class to the above, was used as a standard of reference

* " The Comparative Sensitiveness of Some Common Detectors Used in Radio-telegraphy," by L. W. Austin, " Bulletin " of Bureau of Standards, Washington, Vol. 6, pp. 527-542 ; and " Electrical Review and Western Electrician," Vol. 58, pp. 294-296, February, 1911.

" Electrothermal Phenomena at the Contact of Two Conductors, with a Theory of a Class of Radio-telegraphic Detectors," by W. H. Eccles, " Proc." Physical Society of London, Vol. 25, pp. 273-293.

" Crystal Rectifiers," by G. W. Pierce, " Physical Review," Vol. 29, pp. 478-484 ; " Science Abstracts," Vol. 13A, No. 163 and Vol. 12A, No. 1295.

" Coherers," by W. H. Eccles, " Phil. Mag.," Vol. 19, pp. 869-888 ; " Electrician," Vol. 65, pp. 724-727 and 772-773, August, 1910.

" Theory and Practice of Wireless Detectors as at Present Used," by S. M. Powell, " Electrical Review," Vol. 68, pp. 11-13 and 72-75.

† " The Principles of Electric Wave Telegraphy and Telephony," by Dr. J. A. Fleming, 2nd edition, p. 480.

for the measurement of sensitiveness in each case. Magnetic or closed-circuit transmitters and receivers were used throughout to minimise interference with other apparatus in the laboratory.

Preliminary experiments (particularly with the carborundum detector) were carried out, using the "tilting-coil" method of testing detectors,* employing a square coil of 2 ft. side, and eight turns at the transmitter, included in an oscillation circuit containing a condenser and a quenched spark gap of the rotary (modified Peukert) type, described in the "Proceedings" of the Physical Society of London,† fed from an induction coil with an automatic sender in the primary circuit. At the receiver a rectangular coil, pivotted horizontally, was connected to a variable air condenser to tune it to the transmitter, while the detector under test was connected in series with a double headpiece 2,000-ohm telephone receiver, as a shunt to the tuning condenser. In the same circuit was included a potentiometer to inject a variable direct-current boosting voltage, with a microammeter to measure the current passing, and a high-resistance moving-coil voltmeter to measure the voltage impressed on the circuit by the potentiometer.

The sensitiveness of the detector was measured relatively in these tests by finding the angle between two positions of the tilting-coil at which the sounds in the phones just ceased—*i.e.*, the "angle of silence"—and taking the sensitiveness as proportional to the co-secant of half of this angle—that is, as inversely proportional to the projected area of the receiving coil normal to the wave. This, it was found, does not give strictly accurate results, as with very sensitive detectors it was possible to obtain sounds in any position of the coils—even when the transmitting and receiving coils were at right angles.

It was later found necessary to measure the actual voltage on the terminals of the crystal or detector in use, on account of the drop in the telephones, &c., which amounted in some cases to a considerable fraction of a volt. This was most conveniently carried out by means of a potentiometer, and for this purpose a special one was constructed enabling voltages up to

* "The Production of Steady Electrical Oscillations in Closed Circuits, and a Method of Testing Radio-telegraphic Receivers," by J. A. Fleming and G. B. Dyke, "Proc." Physical Society of London, Vol. 21; and "Phil. Mag." May, 1909.

† "The Measurement of Energy Losses in Condensers Traversed by High-Frequency Electric Oscillations," by J. A. Fleming and G. B. Dyke, "Proc." Phys. Soc. Lond., Vol. 23, p. 117, 1910.

25 or 30 volts to be measured with an accuracy of 0·001 volt or less. The microammeter employed for the current measurements took the form of a Paul single-pivot galvanometer used shunted, when so required, by a resistance box, the currents corresponding to the deflections being obtained from a calibration of the instrument by means of a potentiometer.

On account of the unreliability of the sensitiveness measurements made with the "tilting-coil" method, experiments were conducted with a view to finding a more satisfactory method. The scheme finally used consisted of two flat spiral coils mounted vertically, and having 15 turns of 3/22-wire each, of mean radius 7·25 cm., and inductance 36,000 cm., one coil being fixed (used as the transmitter) and the other mounted so that it could be moved, in guides, to varying distances from the fixed coil. The range of motion of the two coils was about 1 metre.

These coils could be accurately calibrated by sending known alternating currents through the transmitting coil, and measuring the current induced in the receiving coil at different distances from the transmitter. This was done with alternating current at about 1,000 cycles per second from a high-frequency alternator, and the calibration curve of the coils was plotted as the ratio $\frac{\text{received current}}{\text{transmitting current}}$ against scale distance between the coils. The current in the transmitting coil was measured on suitable (calibrated) thermal ammeters,* the received currents being obtained on a vacuum thermo-ammeter and sensitive galvanometer.

The calibration so obtained gives a regular curve, but one which does not follow a very simple law, as the index of the curve (deduced from log. curves) varies from —1 to —3, at short distances the received current falling off inversely as the distance, at slightly greater distances inversely as the square, and at still greater distances at an increasing power which tends towards the cube as a limit.

When obtained in this manner, the above calibration curve also gives the ratio of the voltages on the terminals of the transmitting and receiving coils, and hence serves to compare the sensitiveness of two detectors by drawing out the moving coil until the sounds in the telephone connected to the detector under test are just extinguished in each case, the curve then

* *See* "Journal" Inst. Elec. Engineers, Vol. 44, p. 352.

giving the ratio of the oscillatory voltages impressed on the detectors; and hence, if one of them (say, the Marconi magnetic detector) is taken as a standard, the relative sensitiveness of the other can be determined.

As source of oscillations, experiments were conducted with various arrangements of buzzers and buzzer contacts (any kind of spark-gap being quite out of the question on account of the short distance between the coils), but very successful results as far as stability and reliability goes could not be obtained. The most satisfactory arrangement, finally adopted, was a small eight-part commutator mounted on the shaft of a small motor running at about 3,000 revs. per min., with two gauze brushes pressing on it, and connected as shown in Fig. 1, the brushes being arranged to give alternate periods of "make" and "break." This arrangement was found to be much more

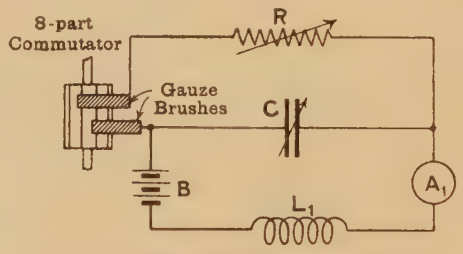


Fig. 1.—Transmitting Connections.

steady in operation than the buzzer method employed by Austin for similar purposes.*

The strength of the signals transmitted could be regulated by means of the resistance R, and kept constant during a test by the indications of the thermal ammeter A_1. L_1 is the transmitter of the sliding coil arrangement and L_2 the receiver.

At the receiver provision was made for quickly changing over from the Marconi magnetic to the crystal or other detector under test, and vice versa, and also for changing over the telephones from one to the other (Fig. 2). It was found advisable to insert a key at K_1 to determine the exact position of silence in the 'phones. The crystal detectors were connected across D_1 and D_2, and when valves were being used, the valve

* "The Comparative Sensitiveness of Some Common Detectors of Electrical Oscillations," by L. W. Austin, "Bulletin" of the Bureau of Standards, Washington, Vol. 6, p. 528.

filament was put across V_{f-} and V_{f+}, and the plate connected to V_p. The moving coil voltmeter V served to adjust the voltage on the filament to the correct value, by means of the variable resistance R_3. Western Electric 2,000-ohm double headpiece telephones were used for all the tests.

The majority of the crystals were clamped in a holder comprising two brass plates, through a hole in one of which a portion of the surface of the crystal is exposed, on to which a contact of metal or another crystal can be pressed.

At the commencement of each test the strength of the transmitted signals was adjusted until the signals received on the

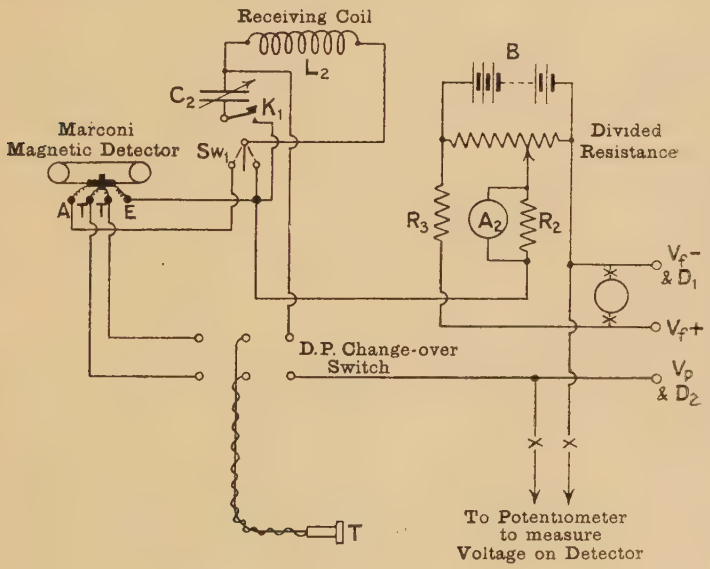


FIG. 2.—RECEIVING CONNECTIONS.

magnetic detector were just extinguished at a predetermined point on the scale of the sliding coils, and the sensitiveness tests then made on the second detector at various boosting voltages, the currents being measured in each case to enable the characteristic curve to be plotted. In this manner the "personal equation" due to the varying sensitiveness of the ear was eliminated.

As a preliminary experiment with this method the sensitiveness of a series of detectors, used as rectifiers only—*i.e.*, without boosting voltage—was measured, the most sensitive point

on each crystal being found for this (*see* table below). This shows the " Perikon " or zincite-chalcopyrite detector to be the most sensitive of those tested when used as a simple rectifier. The table also gives the maximum measured values of the sensitiveness for the various detectors tested when used with boosting voltages.

Table showing the Relative Sensitiveness of Various Detectors.

Detector.	Maximum sensitiveness when used as simple rectifiers.	Maximum measured sensitiveness with boosting voltage.
Marconi magnetic, assumed as unity	...	...
Molybdenite-copper point	2·15	2·15
Graphite-steel point	1·26	...
Carborundum, one end set in solder	0·50	0·60
Carborundum, not set in solder	0·325	1·0
Galena-plumbago	8·35	12·6*
Zincite-copper point	6·6	...
Zincite-brass point	3·43	...
Chalcopyrite-copper point	0	...
Chalcopyrite-brass point	0	...
" Perikon " (zincite-chalcopyrite)	10·5	12·1
Bornite-copper point	1·0	...
Bornite-carbon point	0	...
Zincite-bornite	7·4	7·4
Fleming carbon-filament valve (No. 12)	...	1·0
Fleming 12-volt metal-filament valve	...	1·0
Fleming 15½ volt metal-filament valve (No. 33)	...	12·0
Tellurium-aluminium	...	0·9
Electrolytic (German make)	...	1·0
Electrolytic-nitric acid	...	4·0

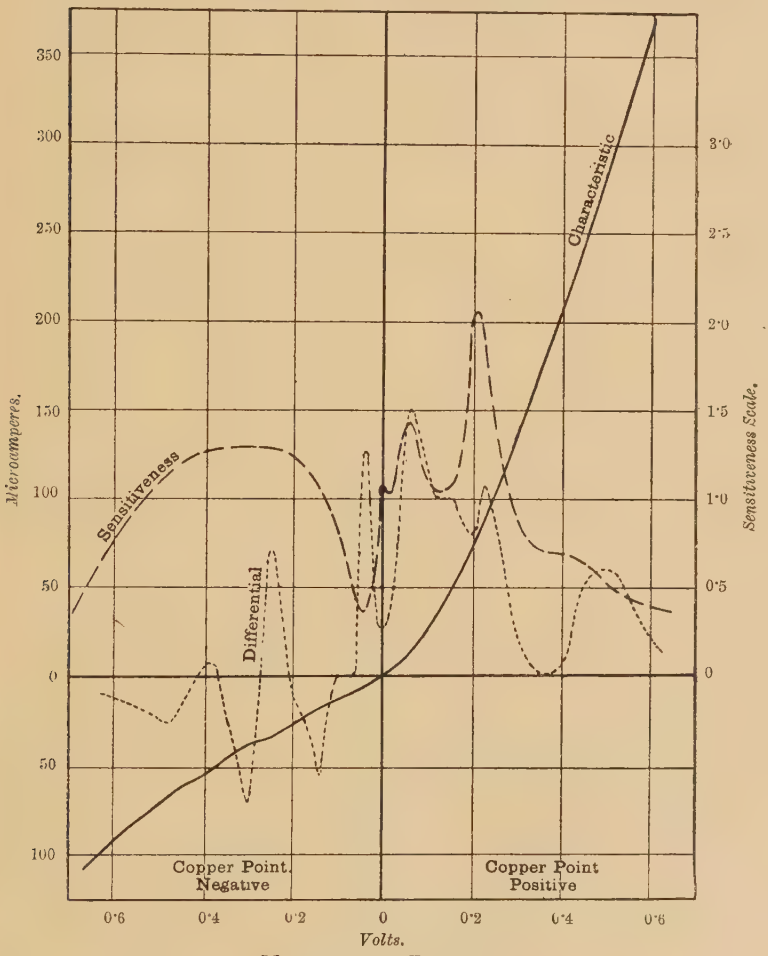
* Note.—If the *general shape* of the sensitiveness curve for the galena detector may be assumed to remain the same for very light contact as for firmer contact (with which the above measurements were taken), the maximum *estimated* sensitiveness for this detector with very light contact is *of the order of* 60 *to* 70, as compared with the magnetic detector.

Since the exact values of the current, voltage, &c., obtained in these tests for the various detectors will necessarily differ with different crystals, tables giving the results of the measurements are not given, but sample curves are included to show the general form of these results, as the *general shapes* of the curves will probably remain the same for the same substances.

The conditions of these tests should be noted—viz., all the detectors were tested with the same telephone receivers, of 2,000 ohms resistance, and hence the figures given do not necessarily represent those of the best possible conditions, the results being, therefore, not strictly comparable with those of,

say, Dr. Austin, in which the best resistance of telephone was chosen for each detector, conditions not always obtainable in practice.*

It should be noted that whilst the numbers given opposite

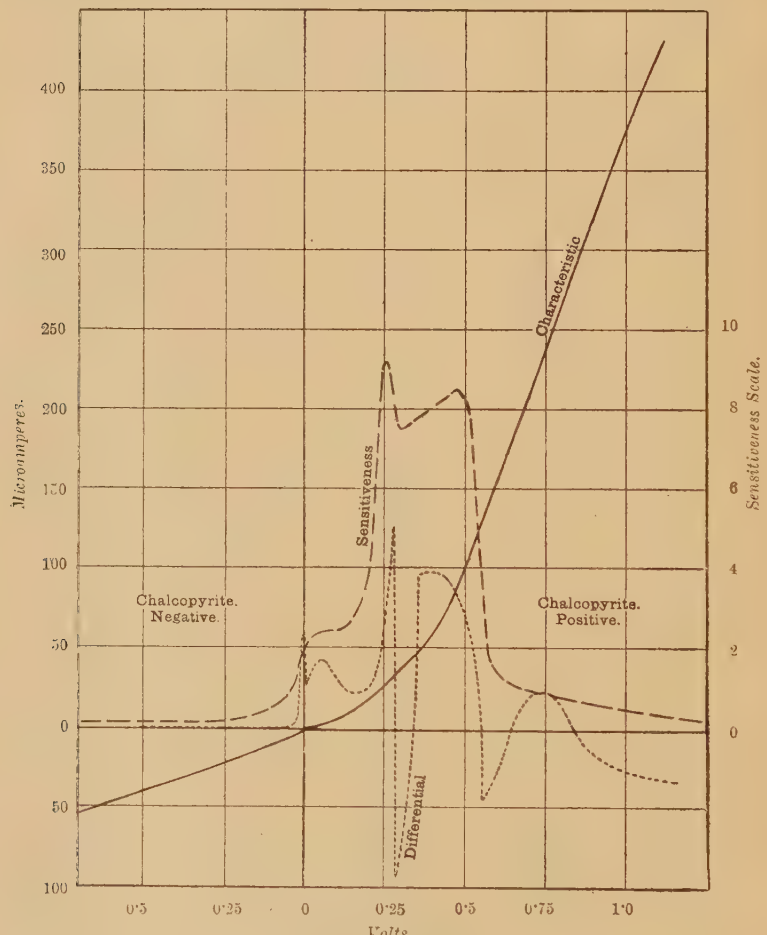


MOLYBDENITE DETECTOR.

each detector in this table indicate the relative sensitivity of these detectors to one another, the true relative sensitiveness

* "The Comparative Sensitiveness of Some Common Detectors used in Radiotelegraphy," by L. W. Austin, "Bulletin" of the Bureau of Standards, Washington, Vol. 6, pp. 527-542, November, 1910.

of the magnetic detector when worked under its own special best conditions would be expressed by a number greater than unity, since it belongs to a different class, being a " current " detector where the others are all " potential " detectors, and,



PERIKON DETECTOR.

therefore, not strictly comparable with them under the same conditions of testing apparatus, its use in these tests being merely for a convenient and reliable standard of comparison for adjusting the apparatus previous to each experiment.

Notes on Curves.

In comparing the sensitiveness and differential curves here given, it should be remembered that as far as the operation of the detector is concerned, it does not matter whether the ordinate of the differential is positive or negative (*i.e.*, whether the current through the telephone is increased or decreased by the application of the oscillation), and hence all negative ordinates of the second differential curve should be reversed in sign and a species of envelope curve drawn in. This curve should then be compared with the sensitiveness curve for any points of resemblance.

Curve I.—Molybdenite-Copper Detector.

On the whole a general sort of agreement may be seen between the sensitiveness and second differential curves, with the exception of the minima in the differential at 0·36 volt positive, and in the neighbourhood of zero voltage, which have no counterparts in the sensitiveness.

Curve II.—" Perikon " or Zincite-Chalcopyrite Detector.

In general shape there is a pretty good agreement between the two curves for this detector. A series of sensitiveness curves taken with this detector show how much the shape of this curve can vary with the particular contact and crystal employed, but, although differing in details of shape and size of maxima, they all show in general form a maximum semsitiveness with about 0·3 to 0·5 volt, chalcopyrite positive.

Curve III.—Zincite-Bornite Detector.

The agreement between the two curves is not quite so good in this case, but the differential, however, shows up the general features of the sensitiveness curve, with the exception of the maximum at 3·5 volts, which is relatively too large.*

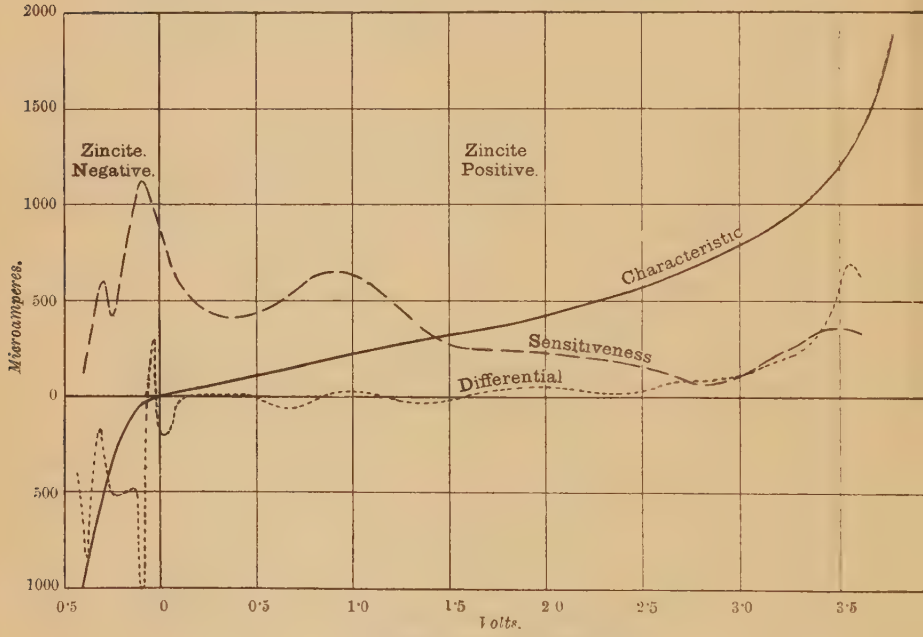
It was found with this detector that subjecting it to a complete cycle of impressed or boosting voltage had a fairly definite effect on the sensitiveness curve, the limits of the cycle being about those of practical working for this detector.

The cycle was commenced at 3·6 volts, zincite +, and carried through zero to — 0·4 volt, and then back to + 3·6 volts, the starting point of the cycle.

It was found that the maximum sensitiveness was unaffected by the cycle, but that a remarkable " kink " occurred in the curve before this maximum sensitiveness was reached on the return part of the cycle, which is not found at all in the first

* *See* also note to Curve VI. for Fleming valve.

half of the curve. This effect was observed on several crystals. It should also be noted that besides affecting the shape of the sensitiveness curve as above, the characteristic curve in the case of most detectors is also altered to a greater or less degree depending on the nature of the crystal employed, and consequently in most instances the characteristic curve for the cycle encloses an area, which is somewhat suggestive of a hysteresis effect, as also noticed by Pierce.*



ZINCITE-BORNITE DETECTOR.

The Tellurium-Aluminium Detector.

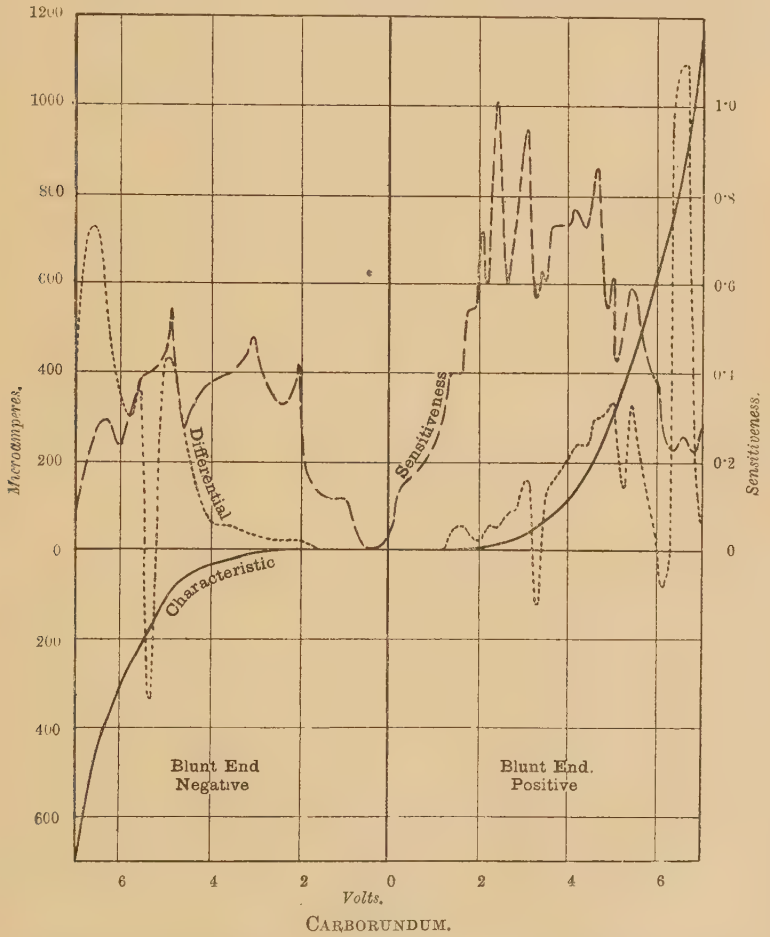
This detector does not show much similarity between the sensitiveness and differential curves; in fact, the largest ordinates of the differential occur where the sensitiveness is zero. This seems to indicate that more than one action is at work, and that in all probability they are acting in opposition, at all events, at zero voltage—otherwise it is difficult to see why such a sudden change of curvature of the characteristic as occurs

* "Crystal Rectifiers for Electric Currents and Electric Oscillations," by G. W. Pierce, "Physical Review," Vol 25, pp. 31-60; also "Conduction of Electricity at Contacts of Dissimilar Solids," R. H. Goddard, "Phys. Review," Vol. 34, pp. 423-451; "Electrician," Vol. 69, pp. 778-781, Aug., 1912.

there should not produce a considerable sensitiveness at that point. This detector also showed a marked tendency to behave like a filings coherer—the reception of a signal often causing its resistance to decrease very considerably.

Curve IV.—Carborundum.

The period of disturbance of the differential roughly coincides with the period of sensitiveness of this detector, but for

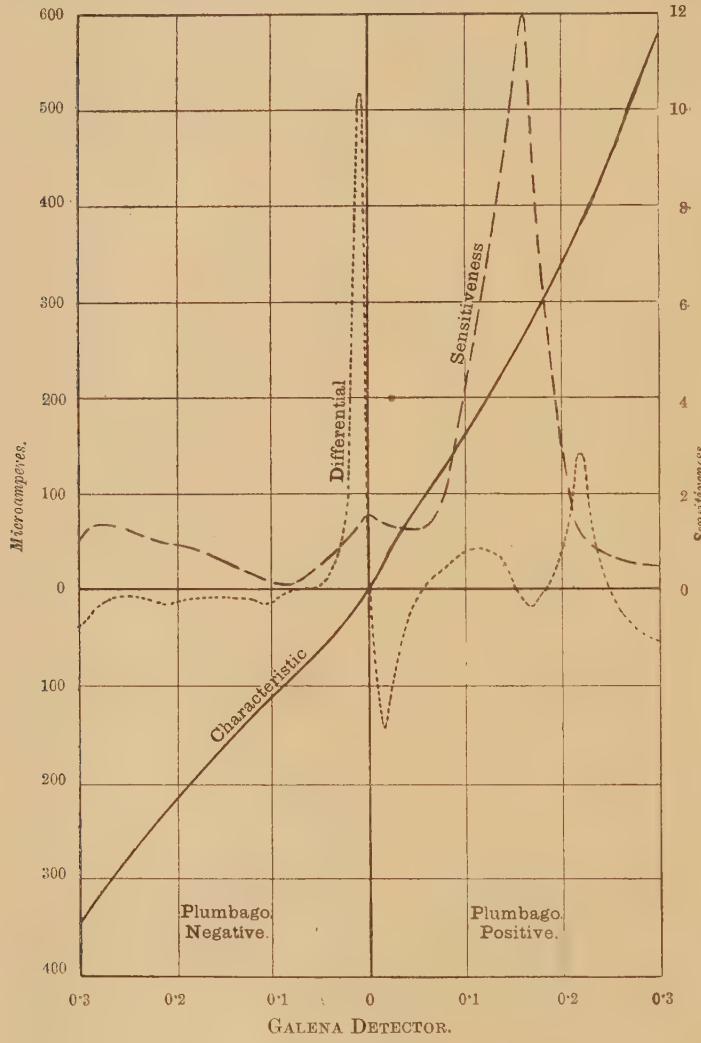


CARBORUNDUM.

both positive and negative voltages the differential shows large ordinates for the high voltages, where the sensitiveness is falling off.

Curve V.—Galena-Plumbago Detector.

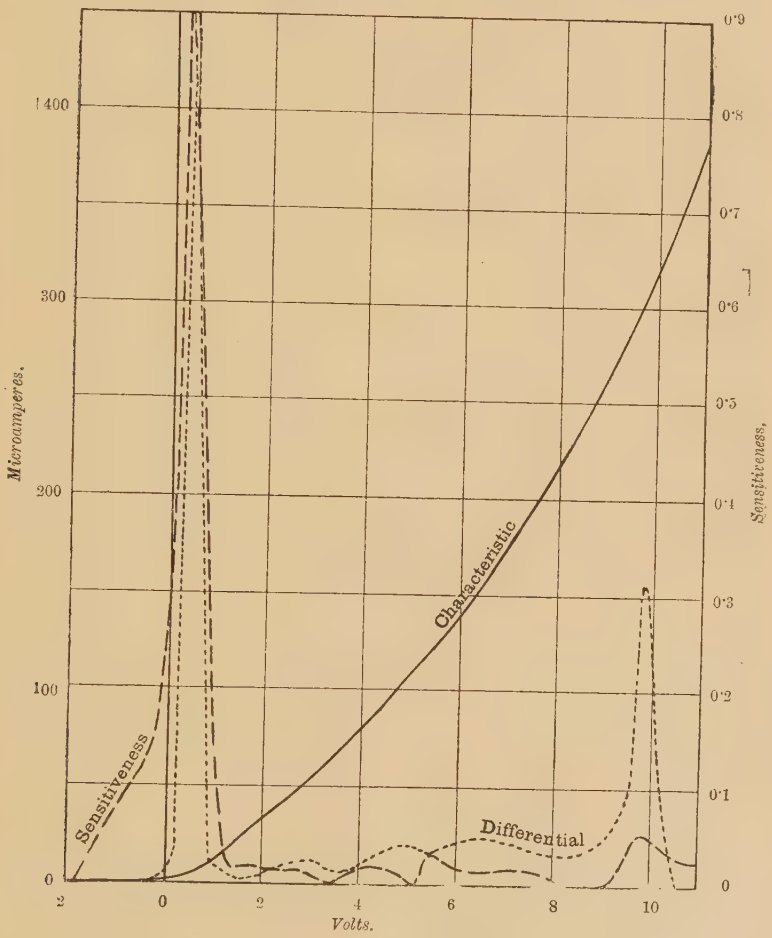
Similar remarks apply to this as to the tellurium-aluminium detector.



Electrolytic Detector.

The detector tested was supplied by a German firm, and was totally enclosed and sealed. Apart from a large ordinate at zero voltage, where the sensitiveness is zero, the region of

disturbance of the differential roughly agrees with the region of maximum sensitiveness of the detector, although individual details do not show up at all. A remarkable bend in the characteristic occurs at zero voltage, although the sensitiveness is there zero.



FLEMING OSCILLATION VALVE—CARBON FILAMENT (12-VOLT).
Voltage measured from Plate to Negative Leg of Lamp Filament.

Electrolytic Detector, with Nitric Acid Electrolyte.

This detector consisted of Wollaston wire dipping into nitric acid. The sensitiveness reached four times the figure for the

previous detector, and a great difference between the shapes of the characteristic curves for these two detectors was noted. Otherwise similar remarks apply as to the previous detector.

Curve VI.—Fleming Carbon-Filament Oscillation Valve.

A curve taken on a 12-volt carbon filament valve is appended to show the agreement that can be obtained between the sensitiveness and differential curves in this case, the similarity between the two curves being very great with the exception of the peak near 10 volts.

This non-agreement between the two curves at high voltages (and, therefore, large currents), which takes the form of the differential curve indications being relatively too large, and which may also be noticed in some of the other curves, may be caused by a falling off of the sensitiveness of the telephone to small variations when large steady currents are passing through it.

To sum up, the curves show that in the majority of cases the second differential of the characteristic gives a good indication of the sensitiveness of the detector, as in the case of the oscillation valve, but that some detectors, notably the galena and electrolytic, seem to show that there are other actions at work which may oppose the one depending on the curvature of the characteristic. Since this also occurs with one of the electrolytic detectors it perhaps points out that this other action may be electrolytic in nature.

An appendix gives reference to a number of recent Papers bearing on this subject, and may perhaps be of some use to those interested in the development of these crystal detectors.

Finally, my best thanks are due to Dr. J. A. Fleming, in whose laboratories at University College, London, and under whose guidance the above tests were carried out.

APPENDIX—REFERENCES.

" Electrothermal Phenomena at the Contact of Two Conductors, with a Theory of a Class of Radio-telegraphic Detectors," by W. H. Eccles, " Proceedings " of the Physical Society of London, Vol. 25, pp. 273-293 ; " Electrician," Vol. 71, p. 900.

" The Heterodyne Receiving System," by J. L. Hogan, jun., " Electrical World," Vol. 61, p. 1298, 1913.

" Electric Wave Detectors," " Lumière Electrique," Vol. 22, pp. 341-343 ; French patent 452,062 ; " Science Abstracts," Vol. 16B, Abstract Nos. 791.

" Note sur la Théorie du détecteur Eléctrolytique," by J. Rodet, " Revue Télégraphie sans fil," Part 4, p. 17, Part 6, p. 26, June, 1913.

" The Measurement of Received Radio-telegraphic Signals," by L. W. Austin, " Journal " of the Washington Academy of Science," Vol. 3, pp. 133-137, March, 1913.

" Crystals as Rectifiers and Detectors," by A. E. H. Tutton, " Wireless World," Vol. 1, pp. 232-239, July, 1913.

" Rectification by Photo-electric Cells," by S. H. Anderson, " Physical Review," Vol. 1, Series 2, pp. 222-232, March, 1913.

" Some Characteristic Curves for Gases at Low Pressures," by R. F. Earhart, " Physical Review," Vol. 1, Series 2, pp. 85-95, Feb., 1913.

" Experimental Determination of the Internal Resistance of a Thermo-Cell Detector under Working Conditions," by A. K. Kleinschmidt, " Jahrbuch der Drahtlosen Telegraphie," Vol. 6, pp. 407-413, Jan., 1913; " Science Abstracts," Vol. 16B, Abstract No. 567.

" The Resistance of Metallo-Crystalline Junctions," by A. Wesely, " Physikalische Zeitschrift," Vol. 14, pp. 76-81, Jan., 1913; " Science Abstracts," Vol. 16A, Abstract No. 673.

" Le Mercure dans les Détecteurs de Télégraphie sans fil," by P. Jégou, " Revue Télégraphie sans fil," Part 1, pp. 5-7, Part 2, pp. 12-14, Jan., 1913.

" Principles of Electric Wave Telegraphy and Telephony," by J. A. Fleming, 2nd edition, Chap. 6, pp. 417-484. (Contains numerous references to other Papers, &c.)

" Principles of Wireless Telegraphy," by G. W. Pierce, 1st edition, Chaps. 16-19, pp. 140-214.

" The Incandescent Filament Wireless Detector, and a New Type of Detector based upon Thermo-ionic Emission," by Q. Majorana, " Accad. Lincei Atti," Vol. 21, pp. 235-239 and 274-277, Sept., 1912; " Science Abstracts," Vol. 16B, Abstract No. 452.

" The Bunsen Flame as a Wireless Detector," by G. Leithauser, " Phys. Zeitschrift," Vol. 13, pp. 892-894, Sept., 1912; " Science Abstracts," Vol. 16A, Abstract No. 230.

" The Conduction of Electricity at Contacts of Dissimilar Solids," by R. H. Goddard, " Physical Review," Vol. 34, pp. 423-451, June, 1912; " Electrician," Vol. 69, pp. 778-781, Aug., 1912.

" The Production of Rectifiers (Detectors) by Physical Means," by H. Sutton, " Electrician," Vol. 69, pp. 66-67, April, 1912, and G. W. Pickard, " Electrician," Vol. 69, p. 232, May, 1912.

" The Use of Valves for Reducing Atmospheric Disturbances," " Electrician," Vol. 68, p. 466; British patent, 20,441/10; " Marconigraph," Vol. 1, Part 9, p. 5, Dec., 1911.

" The Operation of Detectors in Wireless Telegraph Service," by L. H. Harris and J. L. Hogan, jun., " Electrical World," Vol. 58, pp. 1602-1604, Dec., 1911, and " Electrical World," Vol. 59, p. 153.

" Vacuum Oscillation Valves," by R. S. Willows and S. E. Hill, " Electrician," Vol. 68, pp. 302-303, Dec., 1911.

" Measuring Instruments depending on Heat Effect—the Barretter," by M. K. Grober and H. Zöllich, " Phys. Zeitschrift," Vol. 12, pp. 1048-1053, Nov., 1911.

" The Stratified Structure of Tin Ores and Crystal Action," by T. Liebisch, " Preuss. Akad. Wiss.," Berlin, Sitz. Ber. 18, pp. 414-422.

" New Means for Receiving Electric Waves in Wireless Telegraphy," " Engineer," Vol. 112, p. 191; British patent, 8,387/11.

" The Slipping Contact-rectifying Detector," by L. W. Austin, " Journal " of the Washington Academy of Science, Vol. 1, pp. 8-9, July, 1911; " Phys. Zeitschrift," Vol. 12, pp. 867-868, Oct., 1911; " Science Abstracts," Vol. 15B, Abstract No. 67, and Vol. 10A, Abstract 1,391.

" Detectors for Wireless Telegraphy and Telephony," by E. Nesper, " Jahrbuch der Drahtlosen Telegraphie," Vol. 4, pp. 312-326, 423-438 and 534-557, 1911.

" Unidirectional Conductivity of Contact Detectors," by G. Leimbach, " Phys. Zeitschrift," Vol. 12, pp. 228-231, April, 1911; " Science Abstracts," Vol. 15A, Abstract No. 385.

" The Mode of Conduction in Gases illustrated by the Behaviour of Electric Vacuum Valves," by O. Lodge, " Philosophical Magazine," Vol. 22, pp. 1-7, July, 1911.

" Reinforcing Signals in Wireless Telegraphy," by H. A. Hall, " Electrical Review," Vol. 68, p. 51, Jan., 1911.

" The Theory and Practice of Wireless Detectors as at Present Used," by S. M. Powell, " Electrical Review," Vol. 68, pp. 11-13 and 72-75, Jan., 1911.

" The Comparative Sensitiveness of Some Common Detectors used in Radio-telegraphy," by L. W. Austin, " Bulletin " of the Bureauof Standards, Washington, Vol. 6, pp. 527-542, Nov., 1910; " Electrical Review and Western Electrician," Vol. 58, pp. 294-296, Feb., 1911.

" The Properties of Detectors used in Wireless Telegraphy," by K. Bangert, " Phys. Zeitschrift," Vol. 11, pp. 123-130, Feb., 1911; " Electrician," Vol. 66, p. 11-13, Oct., 1910.

" An Electrolytic Detector," by J. E. Ives, " Jahrbuch der Drahtlosen Telegraphie," Vol. 4, pp. 112-117, Sept., 1910; " Phys. Zeitschrift," Vol. 11, pp. 1181-1183, Dec., 1910; Science Abstracts, Vol. 14A, Abstract No. 951.

" The Sensibility of Wireless Telegraphy Detectors and Damping Factor," by H. H. Gordon, " Electrical Review and Western Electrician," Vol. 57, pp. 536-538, Sept., 1910.

" Coherers," by W. H. Eccles, " Philosophical Magazine," Vol. 19, pp. 869-888, June, 1910; " Electrician," Vol. 65, pp. 724-727 and 772-773, August, 1910.

" The Action of Metallic Contacts on a Filings Coherer," by B. Szillard, " Comptes Rendus," Vol. 150, pp. 1670-1672, June, 1910; " Science Abstracts," Vol. 13A, Abstract No. 1,133.

" Unilateral Conductivity in Fleming Oscillation Valve," by R. Ichinohe and M. Kinishita, " Memoranda " of the College of Science and Engineering, Kyōtō, Vol. 2.4, pp. 107-119, 1910; " Science Abstracts," Vol. 13A, Abstract No. 1,487.

" Electrical Oscillation Detector actuated solely by Resistance Temperature Variations," by W. H. Eccles, " Philosophical Magazine," Vol. 20, pp. 128-134, July, 1910; Paper read before Physical Society, May, 1910.

" A New Form of Magnetic Detector of Electric Oscillations," by R. Arnò, " Accad. Lincei Atti," Vol. 19, pp. 805-809, June, 1910; " Science Abstracts," Vol. 13A, Abstract No. 1,632.

" Energy Relations in Wireless Telegraphy Detectors," by W. H. Eccles, " Philosophical Magazine," Vol. 20, pp. 533-538, Sept., 1910; Paper read before the Physical Society of London, July, 1910; "Electrician," Vol. 66, pp. 166-168, Nov., 1910.

" Investigation of the Barretter in Oscillatory Circuits," by W. Kempe, " Phys. Zeitschrift," Vol. 11, pp. 331-337, April, 1910; " Science Abstracts," Vol. 13A, Abstract No. 1,136.

" An Electrolytic Detector operating without Auxiliary E.M.F.," by P. Jégou, " Comptes Rendus," Vol. 150, pp. 1307-1308, May, 1910; " Science Abstracts," Vol. 13B, Abstract No. 628.

" Crystal Rectifiers," by G. W. Pierce, " Physical Review," Vol. 29, pp. 478-484, Nov., 1909; Vol. 28, pp. 153-189; Vol. 25, pp. 31-60; " Proceedings " of the American Academy of Arts and Sciences, Vol. 45, p. 317, 1909.

" The Sensibility of Barretter Arrangements," by H. Zöllich, " Phys. Zeitschrift," Vol. 10, pp. 899-902, Nov., 1909; " Science Abstracts," Vol. 13A, Abstract No. 743.

" Thermo-electric Properties of some Minerals," by M. Kimura, K. Yamamoto and R. Ichinohe, " Memoranda of the College of Science and Engineering," Kyōtō, Vol. 2.4, pp. 59-61, 1910; " Science Abstracts," Vol. 13A, Abstract No. 1,491.

" Unilateral Conductivity of Minerals in Contact," by M. Kimura and K. Yamamoto, " Memoranda " of the College of Science and Engineering,

Kyōtō, Vol. 2. 4, pp. 63-82; "Science Abstracts," Vol. 13A, Abstract No. 1,492.

"Sensibility of the Barretter," by B. Gáti, "Phys. Zeitschrift," Vol. 10, pp. 897-899, Nov., 1909; "Science Abstracts," Vol. 13A, Abstract No. 722.

"Crystal and Solid Contact Rectifiers," by A. E. Flowers, "Physical Review," Vol. 29, pp. 445-460, Nov., 1909.

"Imperfect Contact Detectors operating without Auxiliary E.M.F.," by P. Brenot, "Lumière Electrique," Vol. 8, pp. 256-268, Nov., 1909; "Science Abstracts," Vol. 13B, Abstract No. 99.

"Experience with Crystal-type Detectors," by L. W. Thomas, "Electrical World," Vol. 54, pp. 1234-1235, Nov., 1909.

"The Electrolytic Detector studied with the aid of an Oscillograph," by G. W. Pierce, "Physical Review," Vol. 29, p. 56, July, 1909.

"A Tantalum Wave Detector and its Applications in Wireless Telegraphy and Telephony," by L. H. Walter, "Proceedings" of the Royal Society, A, Vol. 81.

"Detector for Very Small Alternating Currents and Electric Waves," by L. W. Austin, "Bulletin" of the Bureau of Standards, Washington, Vol. 1, p. 435.

"The Electric Properties of Crystals," by G. W. Pierce and R. D. Evans, "Proceedings" of the American Society of Arts and Sciences, Vol. 47, p. 793.

"The Platinum Point Electrolytic Detector of Electric Waves," by L. W. Austin, "Bulletin" of the Bureau of Standards, Washington, Vol. 2, p. 261, 1906.

"Some Contact Rectifiers of Electric Currents," by L. W. Austin, "Bulletin" of the Bureau of Standards, Washington, Vol. 5, p. 133, 1908.

ABSTRACT.

The Paper describes some experiments recently conducted on different types of wireless detectors, which were undertaken with a view to finding out whether any definite relation could be traced between the sensitiveness and characteristic (or, volt-ampere) curves of a detector, such, for example, as has been known for some time to exist in the case of the Fleming oscillation valve detector between the sensitiveness curve, and a curve plotted from the second differential of the characteristic of the valve.

A table giving the maximum measured sensitiveness of the various detectors tested both when used as simple rectifiers as well as with a steady boosting voltage, shows that of the ordinary crystal detectors the "Perikon" or zincite-chalcopyrite combination has the greatest sensitiveness for ordinary stable adjustments, but that the galena-plumbago detector may greatly surpass it when used with extremely light contact, although in this condition it is of necessity not so reliable as the Perikon, which can be used with a fairly good contact pressure between the crystals.

Sample curves for some of the most common detectors are included in the Paper and show that in some cases a fairly good agreement exists between the sensitiveness curve of a detector and the second differential of its characteristic, this being most notably the case in the more stable of the crystal detectors, but at the same time it is abundantly evident that the flexure of the characteristic curve cannot be the only cause of the response of a detector to wireless signals, but that at least a second action must also be present, as in some cases—notably the electrolytic detector—it was observed that the

maximum ordinates on the second differential, *i.e.*, the point of greatest change of flexure of the characteristic curve, were at places where the measured sensitiveness was either zero or extremely small, showing that there are probably at least two actions opposing one another at this point. As this is most prominent in the case of the electrolytic detector, it perhaps suggests that this additional action when present in other detectors is electrolytic in nature, or that the received oscillations when superimposed on the direct-current boosting voltage partake of the properties of some " trigger " action (such as in the Zehnder trigger cymoscope). This view is supported by experiments with detectors of the tellurium-aluminium type.

In the course of the tests it was found necessary to spend some time in devising a suitable and reliable means of testing these detectors in a quick and easy manner. The " tilting coil " method, due to Dr. J. A. Fleming, described before this Society in 1909, was used as a starting point in the investigation, but was found not to be altogether satisfactory as with very sensitive detectors no position of silence could be found, thus demonstrating the inaccuracy involved in taking the received energy as proportional to the projected area of the receiving coil parallel to the plane of transmitter. The arrangement finally adopted, which may be called the " sliding coil " method, consists of two flat spiral coils mounted vertically, one (the transmitter) being fixed and the other capable of sliding horizontally along a scale.

The transmitting coil was excited by a buzzer contact, and the receiving coil was tuned to the same frequency by means of a variable air condenser. The detector and receiving telephones were connected across this condenser. This method has the advantage of enabling a very accurate calibration of the coils to be obtained using measured high-frequency alternating current. The calibration curve is then used to find the sensitiveness of any detector under test by drawing out the receiving coil until silence is obtained in the telephones and taking one detector (in these tests the Marconi magnetic) as a standard of comparison in each case. In this way the " personal equation " due to the experimenter and variations of ear sensibility may be almost completely eliminated.

DISCUSSION.

Prof. J. A. Fleming thought it was impossible to avoid speculation in connection with these interesting effects. He thought the real cause of the asymmetry in the case of valve-detectors was the emission of electrons from the hot filament. The laws governing this emission had been shown to be analogous to those governing the evaporation of water. Consequently it could be increased by applying a negative pressure. Some of the irregularities observed might be the equivalent phenomenon to boiling with bumping. He thought it would be of interest if Mr. Coursey's experiments could be repeated at different temperatures.

Mr. W. Duddell thought the investigation was extremely difficult, as one could not be certain that a given pair of crystals would always work in the same way. As far as the crystal detectors were concerned, he did not think the relation between the sensitiveness and the second differential of the characteristic curve was very clear. The determination of the second differential curve was very difficult unless the original observations could be reproduced very accurately.

Dr. W. Eccles thought that the agreement between the characteristic curves given in the Paper and those given for the same pairs of substances by previous experimenters showed that the shapes of the curves were undoubtedly dependent on the physical properties of the substances more than on the configuration of the contact. A theory of the cause of the shape of the characteristic curve had been published. The present Paper dealt, however, with quite a different matter, namely the connection between the shape of the curve and the sensitiveness of the detector; the theory of this was also known and was chiefly a matter of geometry. This geometrical theory yielded the following conclusions: First, if the sensitiveness of a detector was measured by the proportion of alternating current rectified, the sensitiveness was greatest near sharp bends of the characteristic curve, that was to say, where the second differential coefficient was largest, though not exactly at that point. Second, if the sensitiveness was measured by an energy method, it was a maximum at a point between the steepest part of the curve and the maximum of the second differential coefficient. It was probable that the first type of sensitiveness was involved in this Paper, and thus on the whole the geometrical theory was corroborated.

Mr. D. Owen asked what the measure of sensitiveness adopted by the author was; also if he could furnish figures as to the actual voltage across the contact at limiting silence in the telephone. He would suggest that prediction of the sensitiveness of a particular individual detector might be more simply made from inspection of an *alternating* voltage characteristic—that was, from a graph in which the direct current through the contact under an alternating low-frequency voltage was plotted as ordinate against the alternating volts as abscissa. This amounted to integrating the two distinct effects observed in direct voltage characteristics, namely, the non-linear property and the asymmetry for positive and negative voltages. Sensitiveness of a detector might be expected to be measured simply by the slope of the straight line joining the origin to a point on the alternating characteristic. A slide was shown of the knee-shaped alternating characteristics obtained from a galena-chalcopyrite contact.

Dr. R. S. Willows thought the characteristic curve given for the oscillation valve was not a good one for the purpose. In his experience of the valve, the detector was most sensitive when the voltage was boosted up until it was just at the point of producing ionisation by collision, to which the second rapid rise in the curve was due. By making use of the electronic emission from hot lime a better cathode was obtained than in the case of the carbon filament.

Prof. G. W. O. Howe thought too much weight had been attached to slight changes in the characteristics of the crystal detectors. A minute alteration in the point of contact greatly altered the properties of the detector. It would be interesting to hear if Mr. Coursey had repeated his observations. Sometimes a polarising voltage greatly improved the sensitiveness while the slightest shifting of the point might render the polarising voltage quite useless. Since they were so sensitive to slight changes in the conditions, much stress should not be laid on little variations in the characteristic. If two detectors were used side by side, it might happen that one of them was most sensitive to waves sent out from one station, while the other might be most sensitive to those from some other station.

Mr. E. H. Rayner thought that some of the irregularities in the characteristics might easily be due to vibration and similar disturbances. He thought it would be useful if the author gave some idea of the resistance of the detectors at maximum sensitiveness, so that one could see if the telephone was doing justice to the detector.

Prof. Fortescue had also found crystal detectors very sensitive to

disturbances, such, for example, as the passing of a motor 'bus near the laboratory, and he thought that slight changes from one characteristic to another, rather than real changes in the characteristic, would account for some of the irregularities shown.

The AUTHOR, in reply, agreed with Dr. Fleming that it would probably be of great value to conduct experiments similar to those described in the Paper at various temperatures, both above and below the ordinary, as in this manner a better insight might be obtained, from the experimental point of view, as to the part played by thermal effects at the contact of the two crystals. The fact that it was unnecessary to have at least one of the contacts of low thermal conductivity was supported by the tests on the tellurium-aluminium detector, in which both materials were metals. These tests seemed to show, however, that the mode of operation of such detectors differed considerably from that of the more ordinary crystal detectors, the type of curves obtained more resembling those of the electrolytic and other detectors in which very little agreement could be traced between the sensitiveness and differential curves. The response of the detector under oscillations seemed in this case to resemble that of a filings coherer, again suggesting something in the nature of a "trigger" action. In reply to Mr. Duddell and Prof. Howe steps were taken in the tests to ascertain to what extent the characteristic curves could be repeated, and it was found that with the "good-contact" detectors, or those operating with moderately firm contact between the crystals, *e.g.*, the "Perikon," almost exact repetition of the curves could be obtained on different occasions, and that although changing the crystals or points of contact altered the scale of the curves, yet in general the main features were present. With the more "imperfect," or "loose-contact," detectors, however, the repetitions were not nearly so good, and it was largely with those detectors that the agreement between the two curves was not so pronounced—possibly for this reason. As mentioned by Dr. Eccles, the process of taking the second differential of the characteristic certainly did magnify the errors of experiment, but as stated in the Paper it was not intended to compare the sensitiveness curve with all the details of the differential, but to draw in a species of envelope curve to the differential. That method would obviously tend to smooth out all superfluous irregularities. The Author was also glad to note that the experimental curves given in the Paper agree with the theoretical ones deduced by Dr. Eccles in his Paper on that subject. It would be of interest if the numerical values of the constants involved in the equations there given could be determined for a particular crystal contact, and the same crystals then tested electrically, and the experimental curve so obtained compared with the theoretical one. The curve shown by Mr. Owen was of interest, but really expressed the response of a detector to signals of various strengths, and did not give the sensitiveness as defined in the Paper. In reply to Mr. Rayner, the lumps in the characteristic cannot well be due to vibration and similar disturbances in the firm contact detectors, while in testing those requiring a lighter contact precautions were taken to insulate the detectors as far as possible from mechanical shocks. The resistance of the detectors at their points of maximum sensitiveness varied from a few hundred to about 10,000 ohms or more, depending on the crystals used.

XI. *A Water Model of the Musical Electric Arc. By* W. Duddell, *F.R.S.*

In the model the arc is represented by a mushroom valve. The pressure of the valve on its seat is so arranged that the pressure tending to re-seat the valve diminishes very rapidly as the valve lifts. Water is admitted beneath the valve, flows through the valve into the vessel which contains it, and overflows. In order to indicate the difference of pressure on the two sides of the valve which represents the arc a glass pressure-column is introduced into the pipe leading to the valve and quite close to it. As the water overflows freely from the tank in which the valve is immersed, the pressure on this side of the valve may be taken as our zero of reference, and consequently the height of the water column in the pressure tube above or below the level of the overflow gives the pressure underneath the valve.

If water be admitted below the valve the pressure in the pressure tube rises to a high value ; finally, the valve lifts, *i.e.*, the arc is struck, but the pressure still remains high. If, however, the flow of water is increased, the valve will open considerably and the pressure below it will decrease. If nicely adjusted this effect can be made to take place over a considerable range.

If instead of connecting a pressure tube of small bore indicating the pressure on the underneath side of the valve a large diameter tube be introduced so that the water column in it has a periodic time of its own and is able to oscillate similarly to the condenser circuit shunting the arc, oscillations will be set up in this column, and if the periodic time of the liquid in this column be altered, the period of the oscillations will be altered ; this can easily be done by connecting air vessels of different capacity to the open end of the tube, so altering the controlling force acting on the water, in other words, altering the capacity of the circuit shunting the arc.

With this water model a great many of the properties of arcs both intermittent and oscillating can easily be shown. The one point of difficulty in constructing the model is to obtain a force acting on the valve which decreases rapidly when the valve lifts and which occasions no friction. So far the only successful method which the author has tried is to hang from the underneath side of the valve a piece of soft iron which nearly touches the pole of a small electromagnet. This gives a force which without any friction rapidly decreases as the valve lifts and works very well.

XII. *Some Further Experiments with Liquid Drops and Globules.* *By* C. R. Darling, *A.R.C.S.*

1. *Communicating Drops.*—An arrangement similar to that used for bringing the interior of two soap bubbles into communication is filled with orthotoluidine, and the extremities placed under water, one being at a lower level than the other. A large drop is formed on the upper branch and a small one on the lower, and on opening the communicating tap the smaller drop passes into the larger one, in spite of the tendency of the larger drop to siphon over into the smaller. When a drop of about half the diameter of the large drop is formed on the lower end, the direction of flow is reversed, the tendency to siphon over now prevailing owing to the diminished curvature of the drop formed at the lower level. A condition of equilibrium between two drops of unequal sizes can be established by trial, and an approximate value of the interfacial tension between the two liquids obtained from the curvature of the drops, and the difference of hydrostatic pressure between them. Orthotoluidine is slightly denser than water below 24°C.

2. *The Structure of Liquid Jets.*—Orthotoluidine is discharged from a cistern through a vertical tube terminating under water, the rate of flow being controlled by a tap. Owing to the slow descent of the escaping liquid, many of the features of a liquid jet, such as the breaking away of drops and their subsequent distortion, are made visible to the eye.

3. *Liquid Spheres Enclosed in a Skin of Another Liquid.*—Aniline is placed beneath a layer of water about 4·5 cm. in height, and a glass tube of 3 mm. bore, open at both ends, is passed through the water into the aniline. On raising the tube, a skin of aniline adheres to the end, and is inflated by the water in the tube, forming a sphere. On removing the tube gently, the sphere remains clinging to the upper surface of the water.

By covering water with a layer of dimethyl-aniline 2·5 cm. deep, and following the same procedure, a sphere of the latter liquid, encased in a skin of water, is formed. On withdrawing the tube, the compound sphere falls to the joining surface of the two liquids, and after remaining there a few seconds is projected violently into the water below into which the skin then merges. The resulting drop of dimethyl-aniline then

rises to the joining surface and breaks through into the upper liquid.

4. *Mixed Vapour and Liquid Drops.*—When a heavy, volatile liquid is heated below water, the vapour bubbles on escaping detach a quantity of the liquid, and the composite drops rise through the water. On nearing the surface the vapour contracts or partially condenses owing to cooling, thus increasing the density of the compound drops, which then sink; but on reaching a warmer level the former density is restored, so that the drops rise again. This process may be repeated several times before the drops reach the surface, when the vapour escapes and the detached liquid falls back into the mass at the bottom. Chloroform shows this action, but monobrombenzene gives the best results.

5. *Expanding Globules.*—When a globule of liquid is floating on the surface of water, and a drop of a second liquid is allowed to fall into it, the globule expands outwards in all directions, often with such violence as to be broken up into several portions. This is well shown when a drop of quinoline is permitted to fall on to a floating globule of dimethyl-aniline.

6. *Combination of Floating Globules.*—Scattered globules of some liquids floating upon water show no tendency to unite; in other cases, however, the contrary holds true. A striking example of the latter is obtained by pouring a quantity of orthotoluidine on to the surface of water, allowing it to break into globules, and then forming a single large globule of dimethyl-aniline on the same surface. The globules of orthotoluidine are absorbed, one by one, by the other large globule, which sends out a protuberance which joins on to the adjacent globule, and then shrinks back into the main mass. This action shows some resemblance to the movements of certain of the lower organisms.

XIII. *On Vibration Galvanometers of Low Effective Resistance.* By Albert Campbell, B.A.

Received December 15, 1913.

Most of the vibration galvanometers in use at the present time have moderately high effective resistance (of the order of 500 ohms). For many purposes a resistance much lower than this is desirable in order to obtain the most sensitive conditions of measurement. Confining my attention to galvanometers of moving coil type, I have recently succeeded in making coils of much lower effective resistance which still give very good current sensitivity. In the earliest vibration galvanometers which I constructed some years ago (1906) small and narrow coils were used, but very soon afterwards I increased the size of the coils in order to increase the area of the mirror and the robustness of the instrument. Due to their comparatively low sensitivity, these early galvanometers had not high effective resistance. By and by Mr. Duddell* so raised the standard of sensitivity with his single loop galvanometer, that he found a very considerable rise of effective resistance due to the back voltage, and he pointed out that this was desirable from the point of view of dynamical efficiency.

Accordingly I reverted to the lighter coils, and the results given in this Paper show the sensitivities that can be obtained by making the coil very small without at the same time unduly diminishing the size of the mirror.

To make the statement of these results clear it is necessary to give first a short account of the mathematical theory. I shall in the main follow Wenner's system,† as he has treated the subject very thoroughly.

If we assume that the damping is proportional to the angular velocity, the equation of motion of the coil is

$$mk^2\ddot{\theta}+b\dot{\theta}+c\theta=gI_{max.}\cos\omega t, \quad . \quad . \quad . \quad . \quad (1)$$

where the symbols have the following meanings :—

mk^2, moment of inertia,

b, damping constant,

* "Phil. Mag.," July, 1909, and "Proc." Phys. Soc., Vol. 21, p. 574.

† "Bulletin" Bureau of Standards, Vol. 6, p. 347, 1910. *See also* Butterworth, "Proc." Phys. Soc., Vol. 24, p. 75, February, 1912, and Haworth, "Proc." Phys. Soc., Vol. 25, p. 264, May, 1913.

c, control constant,
g, deflectional constant,
θ, the angular displacement at time t,
$I_{max.}$, the maximum value (in amperes) of sine wave alternating current (passing through the coil) of frequency n, $\omega=2\pi n$.

When a steady state has been reached

$$\theta=\frac{I_{max.}\, g \sin(\omega t+\varepsilon)}{\sqrt{(c-\omega^2 mk^2)^2+\omega^2 b^2}}, \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $$\cot \varepsilon=\omega b/(c-\omega^2 mk^2). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

If φ is the amplitude, 2φ being the whole angle of vibration of the coil, then

$$\varphi=\frac{I_{max.}\, g}{\sqrt{(c-\omega^2 mk^2)^2+\omega^2 b^2}}=\frac{Ig\sqrt{2}}{\sqrt{(c-\omega^2 mk^2)^2+\omega^2 b^2}}, \quad . \quad (4)$$

where I is the effective value of the current.

Case 1.—If resonance (*i.e.*, maximum φ) be obtained by altering the control c, keeping n_1 the frequency of the source constant, then

$$\omega_1^2=c/mk^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\varphi=gI\sqrt{2}/\omega b \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and $$\varepsilon=0.$$

Case 2.—If resonance be obtained by altering the frequency of the source while c is kept constant, then

$$\omega_2^2=\frac{c}{mk^2}-\tfrac{1}{2}\left(\frac{b}{mk^2}\right)^2=\omega_1^2-\tfrac{1}{2}\left(\frac{b}{mk^2}\right)^2. \quad . \quad . \quad . \quad (7)$$

Case 3.—If the current be cut off, the vibration will gradually settle down to zero, the equation of motion now being

$$mk^2\ddot{\theta}+b\dot{\theta}+c\theta=0, \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and if the free frequency be n_0, we have

$$\omega_0^2=\frac{c}{mk^2}-\tfrac{1}{4}\left(\frac{b}{mk^2}\right)^2=\omega_1^2-\tfrac{1}{4}\left(\frac{b}{mk^2}\right)^2. \quad . \quad . \quad . \quad (9)$$

If the amplitude φ_0 at time $t=0$ falls to φ_2 at time t_2, then

$$t_2=\frac{2mk^2}{b}\log_e\left(\frac{\varphi_0}{\varphi_2}\right). \quad . \quad . \quad . \quad . \quad . \quad (10)$$

When $\varphi_0/\varphi_2=e$, then τ, which we may call the *amplitude time constant*, is given by

$$\tau=\frac{2mk^2}{b} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Hence $$\omega_0{}^2=\omega_1{}^2-\frac{1}{\tau^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11\text{A})$$

and $$\omega_2{}^2=\omega_1{}^2-\frac{2}{\tau^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11\text{B})$$

As Prof. B. O. Peirce* has shown (for a ballistic galvanometer), we can find the value of mk^2/b immediately from equation (10) by observing the time taken for the amplitude to fall to a definite fraction (say $\frac{1}{2}$) of its initial value.

With the very small damping occurring in practice, ω_0, ω_1 and ω_2 are all nearly equal to one another. In what follows I shall consider only the resonance of Case 1.†

Let the moving coil have N turns of mean area s, the flux density in the magnet gap being $\mathfrak{B}$. Also let the following symbols be used :—

h, direct current sensitivity,‡ *mm* at 1 m. per microampere ;
σ, alternating current sensitivity, *mm* at 1 m. per microampere ;
q, alternating voltage sensitivity, *mm* at 1 m. per microvolt ;
R, " dead " resistance of coil ;
R′, effective resistance of coil.

Let the power sensitivity be taken as the square of the deflection (*mm* at 1 m.) divided by the power in micromicrowatts.

Quantities observed.—In testing the coils, the frequency of the source was kept constant (at 100 or 200 ∼ per second), a tuning fork hummer being used as the source. By altering the length and tension of the suspending strips the galvanometer was tuned to resonance and the current and voltage sensitivities σ and q were observed. The effective resistance is given by $R'=\sigma/q$. Then the direct current sensitivity was observed and also the direct current resistance R. Also, when the current was broken, observations were made upon the

* " Proc." American Acad., Vol. 44, No. 2, 1908.

† On the two kinds of resonance, *see* M. Wien, " Wied. Ann.," Vol. 58, p. 125, 1896.

‡ This is half of Wenner's sensitivity, as he defines it for *reversal* of direct current.

dying down deflection, to give τ the amplitude time constant. [This must be kept distinct from the electrical time constant of the circuit.]

Deduction of Constants.—When the coil has a vibration amplitude of φ radians, the scale deflection (*mm* at 1 m.) will be 4,000 φ. It is easy, from the equations given above, to deduce the following relations :—

$$R'=\sigma/q, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$g \doteqdot 9000(R'-R)/\sigma n. \quad . \quad . \quad . \quad . \quad . \quad (13)$$

Also $$g=\mathfrak{B}sN/10, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$c=2g/1{,}000h, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$mk^2=c/\omega_1{}^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$b=\frac{2\sqrt{2ch}}{\omega_1\sigma} \doteqdot \frac{2{\cdot}83c}{\omega_1 . \sigma/h} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Also $$b=2mk^2/\tau. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

We see also that

$$\sigma/h=\omega_1\tau\sqrt{2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

i.e., resonance magnification $\doteqdot$ 8·8 frequency $\times$ (amplitude time constant).

Thus from the observed quantities we can deduce all the constants (mk^2, b, c and g) of the equation of motion. Equation (14) gives an independent determination of g, when the air-gap flux density $\mathfrak{B}$ can be measured and the dimensions of the coil are known. The area s, however, cannot be very accurately measured directly. Approximate direct measurements are included in the table below. The damping constant b can also be determined by two independent methods [equations (17) and (18)].

Results of Tests.—The complete results for a number of coils are given in the following table. These have been chosen so as to show variety in number of turns, size of mirror, magnetic field and resonance frequency. For all the coils unifilar suspensions* of phosphor bronze strip were used, and in most of them the greater part of the resistance R was due to the suspension strips. The magnetic field was produced by a permanent magnet ; it could be altered from 1,650 to 2,500 by inserting a small soft iron pole piece. As the various coils were not all tested in the same region of the air-gap the values

* *See* " Proc." Phys. Soc., Vol. 25, p. 203, April, 1913.

TABLE

Coil	A.	B1.	B2.	C.	D1.	D2.	E1.	E2.	F.	G.	H.	J1.	J2.
N, turns	1·0	2·5	2·5	4·5	4·5	4·5	6·5	6·5	10·5	20·5	40	40	40
s, mean area, sq. cm. (app.)	0·12	0·07	0·07	0·04	0·06	0·06	0·10	0·10	0·10	0·09	0·17	0·07	0·07
Mirror area, sq. mm.	2·1	5·2	2·8	2·1	3·5	3·5	7·2	2·1	16	7·5	5·0	2·9	7·2
Magnet gap $\mathfrak{R}$ (approx.)	1,650	2,500	2,500	2,500	1,650	2,500	2,500	2,500	2,500	2,500	2,500	(1,650)	(2,700)
n_1, resonance freq. $\sim$ per sec.	100	100	200	100	100	100	100	100	100	100	100	100	100
h, direct current sensitivity	0·0095	0·043	0·0146	0·167	0·033	0·047	0·082	0·113	0·080	0·083	0·102	0·105	0·165
σ, alt. current sensitivity	6·9	21·7	10·0	56	21	33	37	50	50	61	130	130	160
q, alt. voltage sensitivity	0·80	1·02	0·62	1·16	1·49	1·07	0·50	0·50	0·285	0·174	0·056	0·167	0·104
Power sensitivity	5·3	22·0	6·2	65·0	31·0	35·0	18·0	25·0	14·0	10·6	7·3	21·0	17·0
R, "dead" resistance, ohms	7·1	6·0	4·6	10·5	5·7	5·7	6·0	6·0	7·0	8·8	14·2	14·5	14·5
R′, effective resist., ohms	8·6	20·1	16·1	48·0	14·1	31·0	74	100	175	351	2,300	780	1,540
σ/h, resonance magnification	725	505	685	335	650	700	450	442	620	740	1,270	1,240	970
10^6mk^2, moment of inertia	10·4	6·9	4·5	1·77	5·6	7·4	10·2	7·6	19·2	31	91	26	26
10^6b, damping constant	25·6	23·2	23·2	9·4	15·5	18·8	40	30	55	75	158	37	49
c, control constant	4·1	2·72	7·1	0·70	2·22	2·94	4·0	3·0	7·6	12·2	36·1	10·1	10·4
g, deflectional constant	19·6	58·5	51·8	60	36·7	69	165	169	303	503	1,840	530	860
τ, amplitude time con., secs	0·81	0·57	0·38	0·38	0·73	0·79	0·51	0·49	0·70	0·83	1·43	1·4	1·1
τ_2, calculated, secs.	0·6	0·4	...	...	0·5	0·6	...	...	...	0·6	1·0	1·0	...
τ_2, roughly observed, secs.	0·8	0·6	...	...	0·6	0·6	...	...	...	0·7	0·9	0·9	...

of $\mathfrak{B}$ are only approximate. A high degree of accuracy was not aimed at in the observations, and hence close consistency is not to be expected in the results. The coils were of various lengths, from 9 mm. to 22 mm.

Remarks on the Results.—It will be seen from the table that it is possible to obtain good current sensitivity with coils having effective resistances as low as 30 or 40 ohms. Also we see by two instances how much the sensitivity depends on the size of the mirror employed. It should be remarked that some of the coils (C for example) are of later and better design than others; thus the average result is not the best that can be obtained. A coil like B1 shows extremely high sensitivity on a low resistance bridge, while one like H is eminently suitable for high resistance or inductance measurements.

The last three lines of the table give the values of the amplitude time constant τ, and also, for several of the coils, τ_2, the time taken for the deflection to fall to half value, as calculated from the other constants and also as roughly determined by actual observations with a stop-watch. The agreement is as near as could be expected. More accurate agreement, however, was got by observing the time taken for the deflection to fall to one-tenth of its initial value.

Selectiveness.—One well-known advantage of resonance instruments is that they are *selective;* they are much more sensitive for the frequency to which they are tuned than for any other. Thus, when harmonic components are preseet in the current, their effect is small. This selective power, however, varies considerably in different instruments. From the constants of any galvanometer the selectivity can readily be estimated (*see* Wenner, *loc. cit.*).

Mr. D. W. Dye has pointed out to me that the current sensitivity is almost entirely determined by the absolute value of the motion time constant. If ω_1 gives resonance, and $\gamma\omega_1$ corresponds to any other frequency, γn_1, then the ratio of the current sensitivities at the frequencies n_1 and γn_1

$$= \sqrt{(1-\gamma^2)^2\omega_1^2(mk^2/b)^2+\gamma^2}. \quad . \quad . \quad . \quad . \quad (20)$$

Usually the first term is much the larger, and hence current sensitivity ratio

$$\doteqdot \pm(1-\gamma^2)\omega_1 mk^2/b$$

$$\doteqdot \pm(1-\gamma^2)\frac{\omega_1}{2}\times(\text{time constant}). \quad . \quad . \quad . \quad (21)$$

Also τ=(resonance magnification)/$\omega_1\sqrt{2}$.

Hence current selectivity for n_1 as against γn_1

$$\doteq \pm(1-\gamma^2)\frac{1}{2\sqrt{2}} \times (\text{resonance magnification}). \quad . \quad (22)$$

Accordingly the magnification (as well as the amplitude time constant) gives an immediate criterion of the selectiveness. The time constant is, however, usually much easier to observe. The table shows clearly that the more massive coils (like H) are the best in this respect. In fact, the more sluggish a galvanometer is, the more selective will it be in current sensitivity. For voltage sensitivity quite different conditions hold, which need not be discussed here; they can be immediately deduced from Wenner's formulas.

ABSTRACT.

The mathematical theory of the motion of the moving coil of a vibration galvanometer is first given (partly following Wenner), and simple relations are shown to hold between the two resonance frequencies, the free frequency and the amplitude time constant. It is also shown how all the constants of the equation of motion can be deduced from observations of the direct and alternating-current sensitivities, the alternating voltage sensitivity and the "dead" resistance. A complete table of the observed and deduced constants is given for a series of very small coils, the number of turns in these varying from 1 to 40. The current sensitivities range from 6 mm. to 160 mm. at 1 m. per microampere at 100 ∿ per second, the corresponding effective resistances being about 9 and 1,500 ohms respectively. It is pointed out that the selectiveness (for given current) due to resonance is mainly determined by the absolute value of the "amplitude time constant"; the more sluggish a galvanometer is in settling to zero the more selective will it be.

DISCUSSION.

Dr. Russell thought everyone was indebted to Mr. Campbell for popularising the resonance galvanometer. In the present Paper the use of the amplitude time constant struck him as being very neat.

Prof. G. W. O. Howe pointed out that one method of determining the no-load losses of a motor was to cut off the supply and observe the rate of slowing down. From this the losses could be calculated, and the efficiency found. This, in effect, was what Mr. Campbell did with the vibration galvanometer, and there seemed to be many analogous points in the two processes.

Mr. Campbell thought Prof. Howe's analogy was extremely good. He added that a coil tested at 50 ∿ per second gave a current sensitivity of 500 mm. at 1 metre per microampere with an effective resistance of 2,500 ohms.

XIV. *Vacuum-tight Lead-seals for Leading-in Wires in Vitreous Silica and other Glasses.* *By* Henry J. S. Sand, *Ph.D.*, *D.Sc.*

Received January 16, 1914.

It is generally accepted that the simplest plan for sealing a metallic conductor through the walls of a glass vessel so as to obtain a vacuum-tight joint consists in employing a metal having as nearly as possible the same coefficient of thermal expansion as the glass. Thus platinum wires are almost universally made use of in the manufacture of vacuum apparatus of all kinds. Suitable nickel-steel alloys are sometimes utilised in a similar manner.

In the case of quartz glass it seems practically hopeless to obtain a metal having the same coefficient of expansion as the glass over the whole range between ordinary temperature and the melting point of the metal or of the glass, and, so far as the author is aware, no really satisfactory method has hitherto been available for obtaining vacuum-tight joints for leading-in-wires in this glass.

We are here confronted with the problem to obtain a joint in spite of the difference of thermal expansion between the materials to be joined, and two main principles appear available for attaining this object.

(1) The elasticity of the metal or of the glass may be utilised. On this principle the author has, *e.g.*, made use of small pieces of elastic steel tube, which were shrunk into lead or soda-glass and several cathode-ray tubes were made, more than three years ago, which have held their vacuum unchanged to the present time.* The applicability of intermediate glass for obtaining seals between a metal having the same expansion-coefficient as the intermediate glass, but a slightly different one from that of the vessel into which the wire is to be sealed, is in a similar manner dependent on the elasticity of the glass.

(2) The plasticity of the metal conductor may be utilised. It appears probable that a method, which was first suggested by Margot,† and further perfected by Bastian,‡ is based mainly on this principle. Here a very thin copper conductor of either

* "Chem. News," 1910, 102, 166.
† Swiss patent, 14288.
‡ Bastian and Calvert patent, 22911/06.

circular or flat cross-section is sealed into lead-glass, the copper evidently being sufficiently plastic to adjust itself to the changes of shape undergone during cooling by the glass.

A method, which appears not to conform to either of these principles, by means of which copper wires were sealed into soda-glass and platinum tubes and wires into Jena-glass has been described by Burnside.* Here the leading-in-wire and the glass are simultaneously chilled by successive short immersions in suitable oils. It is not quite clear on what principle the efficiency of these seals is based, but it seems possible that the solidification of the glass, which, as is known, may be better described as a continuous increase of viscosity, lags behind the decrease of temperature. It may also be taken as certain that the glass in these seals is in a state of very considerable strain. Burnside believes his method to be applicable also to quartz-glass, but it is not apparent how it can be adapted to this purpose. In these seals, as also in those described under (2), it is possible that the volume compressibility and expansibility of the metal may play a certain role.

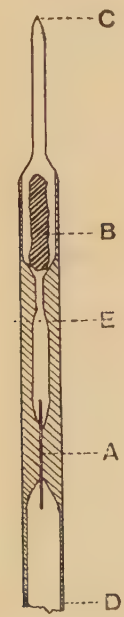
The seals now to be described depend for their efficiency on the high plasticity of lead and on the very great tenacity with which a clean surface of this metal will adhere to vitreous surfaces. The firmness with which clean metal surfaces may adhere to glass when solidified in contact with it has recently been pointed out by P. E. Shaw in a communication on "Sealing Metals" to this Society.†

The method as originally practised by me consisted in making the seal in a high vacuum. The lead was fused and the molten metal was filtered from the solid oxide by allowing it to run through a capillary. It was found desirable to employ three chambers: (1) The chamber in which the metal was melted; (2) a chamber connected with this by a capillary, in which, by agitating it, the metal was freed as much as possible from gas-bubbles escaping in the vacuum from a state of solution; and (3) a chamber in which the seal was made and the metal allowed to solidify. When applying the method to quartz glass a certain amount of difficulty was experienced owing to the fact that the surface of the glass was occasionally not quite smooth, so that, as a result of the high surface-tension of the molten metal, it did not form a perfect contact. This difficulty, as well as the inconvenience resulting from the

*"The Electrician," July 4, 1913.
†Vol. XXIV., 2, p. 95.

dissolved gas, was overcome by the Silica Syndicate by forcing the molten metal into its position by the pressure of the atmosphere. The following is an account of their procedure :—

A quartz tube is shaped as shown in the accompanying sketch and a molybdenum wire placed loosely in position at A and a piece of lead at B. The air is expelled by means of a current of hydrogen and the glass closed at C. The tube is then exhausted from D to a pressure of a few millimetres. The glass at A is now softened and pinched on to the molybdenum wire. The lead in B is then melted and allowed to filter into the space



below which has been highly heated. If necessary this operation may be assisted by shaking and tapping the tube. The end C is now broken off while the metal is still molten so that the atmospheric pressure forces it well against the surface of the glass. The tube may then be cut at E before the lead has solidified and a tinned leading-in wire may be introduced into it.

When made in this manner the seals have so far never been known to fail. They have been fitted to cathode-ray tubes and mercury lamps. They have been heated to the melting

point of the lead, and on solidification of the latter were found to be intact. A quartz-mercury lamp fitted with these seals has now been on test with intermittent burning for more than 500 hours. In another successful test a quartz mercury lamp has been repeatedly immersed in a freezing mixture (about −18 deg.), and then suddenly transferred to tepid water of over 30 deg., the seals being thus subjected to a temperature shock of over 50 deg.

University College, Nottingham, January, 1914.

ABSTRACT.

The author has found that lead which has been allowed to solidify in contact with glass will, if free from oxide, form a vacuum-tight joint with the latter. Owing to the very great firmness with which the metal adheres, and owing to its great plasticity, these joints can stand temperature changes without damage. When applied to quartz, the joints are usually made inside a tube in conjunction with a molybdenum wire seal as follows: The tube is shaped so that the molybdenum wire can be placed loosely inside it. A short piece of the latter is later sealed into the quartz, whereas one of its ends projects a few millimetres into the space in which the lead seal is to be made. Connected with this space by a short capillary there is an upper chamber in which the piece of lead is placed. The air is first blown out with hydrogen, and the tube then closed at the top and evacuated to a pressure of a millimetre or two. The quartz is then softened and pinched on to the molybdenum wire. After this the lead is melted and allowed to filter from oxide through the capillary and run into the space shaped to receive it, which has been highly heated. Before it has solidified, the tube is broken at the top to allow the pressure of the atmosphere to force the lead well against the surface of the glass. The tube is then cut at a suitable place and a tinned leading-in wire introduced into the lead. Such seals have been successfully fitted to vacuum tubes, mercury lamps, &c., and when made as described have so far not been known to fail.

DISCUSSION.

Prof. C. H. Lees asked how the cost of the process compared with that of the ordinary platinum seals in the case of glass.

Dr. Sands, in reply, stated that platinum seals could be made with such small quantities of platinum that it was hopeless to try to compete with them in point of cheapness.

XV. *The Asymmetric Distribution of the Secondary Electronic Radiation produced by X-Radiation.*

By A. J. Philpot, *B.Sc., Layton Research Scholar, University of London, King's College.*

Communicated by Prof. Barkla, F.R.S.

Received January 5, 1914.

It is well known that when X-radiation falls upon a metal such as gold there is emitted from the surface of the metal an electronic radiation sufficient in quantity to produce a considerable ionisation in the neighbourhood of the metal. It is known further that if the metal be in the form of a thin sheet, and the X-radiation pass through the sheet perpendicular to the plane of the sheet, electrons are emitted from both sides of the sheet. It has been found, however, that the amounts of electronic radiation given off on the two sides of the sheet are not equal in such a case; but that, when due allowance has been made for the absorption of the X-radiation in the sheet itself, there is a preponderance of electronic radiation emitted in the original direction of propagation of the X-radiation. This effect has been observed by Cooksey*, Beatty,† and later again by Cooksey.‡ Similar effects have been found in photo-electric work by Stuhlmann,§ and in the production of β-rays by γ-rays by Bragg and Marsden.|| Whilst, however, the results obtained have all shown the existence of asymmetry, there has not been good agreement as regards the extent of the asymmetry, or as regards variation of asymmetry with variation of wave-length in the exciting X-radiation. Thus Beatty found that the ratio of the ionising effect due to ejected electrons in the direction of propagation of the exciting radiation to that in the reverse direction varied from about 1·3 when the exciting radiation was the secondary X-radiation characteristic of tin to practically unity when that from copper or iron was employed. Cooksey, however, in his later Paper, found that the ratio had a constant value of about 1·18 over the same

* "Nature," Vol. LXXVII., p. 509.
† "Proc." Camb. Phil. Soc., Vol. XV., p. 492.
‡ "Phil. Mag." Vol. XXIV., p. 37.
§ "Phil. Mag." Vol. XXII., p. 854.
|| "Trans." Roy. Soc. of S. Australia, Vol. XXXII., May, 1908.

range of exciting X-radiation. Again, Bragg and Marsden found that the lack of symmetry was less for soft γ-rays than for hard, and still less for X-rays which are very soft γ-rays. The order of magnitude of the ratio of emergence to incidence radiation ranged all the way from 20 : 1 down to unity, depending on the nature of the radiations used and the substance in which the secondary rays were excited. Considering the important bearing which this asymmetry has upon our knowledge of the nature of X-radiation it seemed advisable that further experiments should be undertaken; in this Paper such experiments are described.

The apparatus employed is shown in the accompanying diagram (Fig. 1). A beam of X-rays, limited by suitably placed screens, was directed from the anti-cathode K on to

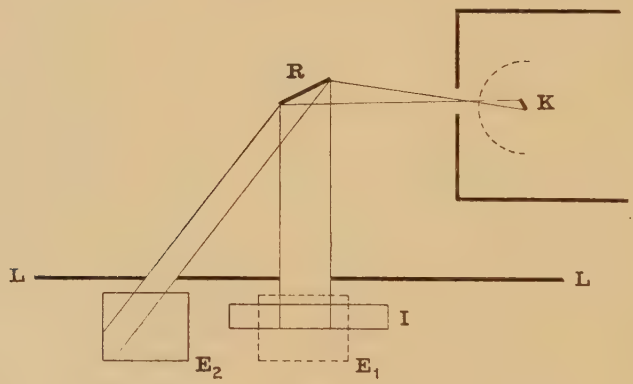


Fig. 1.

a radiator, R, of some desired element. The secondary homogeneous radiation from R was allowed, by means of suitable apertures in a lead screen, LL, to pass (1) through an ionisation chamber, I, (2) into a standardising electroscope, E_2. The ionisation chamber I (Fig. 2) used in these experiments consisted of a metal box of about 2·5 cm. depth, with square ends of about 9 cm. edge. In the centre of the front face of the box a square aperture with edge 4 cm. was cut and the opening covered with thin aluminium. By means of grooves, hollow square aluminium frames could be slid down immediately next to the front and back faces A and B. Three such frames were used during the experiments and on each was stuck a sheet of paper, which was in turn covered with two specially thick gold leaves,

each having a thickness of about 7×10^{-5} cm. Each frame, being hollow, could thus be placed so that either gold leaf or paper faced into the chamber. Between the two faces A and B was placed a square electrode of aluminium wire, crossed by meshes of exceedingly fine aluminium thread, the electrode being of such a size that only the fine mesh was at any time exposed to the radiation from R. The electrode communicated through an ebonite plug with the gold-leaf system of an electroscope, E_1. On passage of X-radiation the rate of leak of E_1 was thus a measure of the ionisation taking place in I, and this was standardised by comparison with the leak in the electroscope E_2. Both electroscopes were of the ordinary Wilson pattern.

The method of procedure was as follows : Two frames were placed in the chamber, the one at A having gold facing into the chamber, the one at B paper. The X-radiation was passed and the ionisation measured. The frames were then taken out

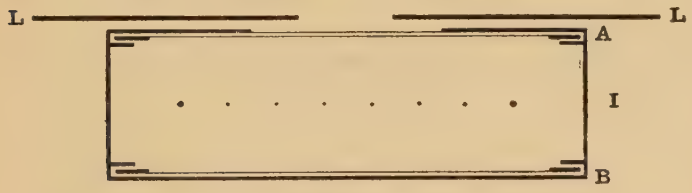


Fig. 2.

and their positions interchanged, the one previously at A being placed at B with the gold again facing inwards and vice versa. The ionisation was again taken. The frame at B was then removed and the third frame put in, having paper facing inwards. The ionisation was again taken. This third ionisation is evidently that due to all effects except the electronic radiation from the gold, this last being absorbed in the paper. Evidently, then, by subtracting this third ionisation from the first and second, we get respectively the ionisation due to the electronic radiation in the direction of propagation of the exciting X-radiation and in the reverse direction. It will be noticed that, as in both cases the same thickness of gold had been traversed, at the surface of the gold the intensity of the exciting radiation was the same, except for a slight absorption due to the passage through the 2 cm. of air in the chamber. Also the electrons were always ejected from the same gold surface, and it was to prevent injury to, or contamination of,

this surface, by contact with either of the faces of the chamber, that the third frame was used. Lastly, the thickness of gold used, $1{\cdot}4\times10^{-4}$ cm., acted, except for extremely penetrating radiations, as an infinitely thick gold plate as regards absorption of the emitted electrons.

A slight correction must be made due to absorption. Let λ_1 be the co-efficient of absorption of the homogeneous exciting radiation in gold. Let λ_2 be the co-efficient of absorption of the electronic radiation in gold, assuming an exponential absorption. Suppose a radiation of intensity I acting over an area A produces in a thickness dt of gold electrons which absorbed in air would give an ionisation A$Iidt$. Considering the case in which the gold faces inwards at A (Fig. 3). Let the

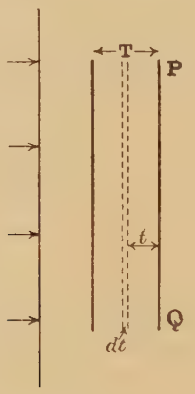


Fig. 3.

intensity at the inmost face PQ be I. If the electrons were not absorbed in the gold the ionisation due to corpuscles produced at a distance t from PQ would be

$$\mathrm{A}Ie^{\lambda_1 t}\,idt.$$

Since the electrons are absorbed, the actual ionisation is

$$\mathrm{A}Iie^{(\lambda_1-\lambda_2)t}\,dt.$$

The total ionisation will be

$$\mathrm{A}Ii\int_0^{\mathrm{T}} e^{(\lambda_1-\lambda_2)t}\,dt,$$

where T is the total thickness of the gold.

This $=\dfrac{\mathrm{A}Ii}{\lambda_2-\lambda_1}$, since $e^{-\lambda_2\mathrm{T}}=0$. Similarly it will be easily seen

that when the gold faces inwards at B the ionisation is $\frac{AIi}{\lambda_1+\lambda_2}$; so that we must increase the ionisation with the gold at B by a multiple $\frac{\lambda_2+\lambda_1}{\lambda_2-\lambda_1}$ in order to compare it with that with the gold at A. The absorption of the exciting X-radiation in the air of the chamber has been ignored, since even with the least penetrating radiation employed the correction involved is negligible.

Four homogeneous radiations were used and the following table gives the results obtained :—

Exciting radiation.	λ_1.*	λ_2.†	$\frac{\lambda_2+\lambda_1}{\lambda_2-\lambda_1}$	Uncorrected ratio.	Corrected ratio.
Mo. $\frac{\lambda}{\rho}$ in Al=5.....	2,142	136,000	1·03	1·15	1·11
Ag. $\frac{\lambda}{\rho}$ in Al=2·5...	1,185	89,000	1·02	1·16	1·13
Sn. $\frac{\lambda}{\rho}$ in Al=1·57..	998	58,000	1·03	1·20	1·16
Ba. $\frac{\lambda}{\rho}$ in Al=0·8 ...	870	33,000	1·05	1·27	1·21

The values thus obtained do not differ in any marked degree from those obtained by Cooksey, but it seemed significant that the gradual rise in the ratio corresponded with a rise in the penetrating power of the exciting radiation. In order to ensure that this rise was not due to a slight loss of electrons to the sides of the chamber when the gold was at B (due to the slight divergence of the exciting beam), which loss would, of course, increase with the hardness of the exciting radiation, the size of the aperture was considerably diminished. Values were obtained which, within the limits of experimental error, were the same as before. Again, to make sure that the variation was not due to a slight variation in the thickness of

* Barkla and Collier, "Phil. Mag.," June, 1912.

† The value of λ_2 for δn was found by taking the value for absorption in air given by Beatty ("Phil. Mag." Vol. XX., p. 324), and calculating from it, assuming the truth of Lenard's law, the value for absorption in gold. The values of λ_2 for the other radiations were obtained by taking λ_2 inversely proportional to the fourth power of the atomic weight of the radiator. (Whiddington, "Proc. Roy. Soc.," Vol. 86, Series A, p. 376.)

the gold leaves, the frames were used to absorb the radiation from copper. No variation in absorption was found.

In order to obtain still harder radiation, and also to make certain that the effect was in no way dependent on the intensity of radiation, two or three values were obtained using the primary radiation from the X-ray bulb. A deeper chamber was used, but the aperture was considerably diminished. The radiation was made to pass through a considerable thickness of aluminium before reaching the chamber, and the mass absorption co-efficient in aluminium of the radiation entering the chamber was found after each experiment :—

Mass absorption co-efficient in Al of radiation (λ/ρ)	Corrected ratio.
0·5	1·24
1·3	1·19
2·5	1·15

Here, again, the same gradual rise occurs.

Summary.

The extent of asymmetry has been investigated with radiations whose mass absorption co-efficients in aluminium vary from 0·5 to 5. Although the values generally do not differ much from the value 1·18 found by Cooksey, yet in general an increase in hardness of the exciting radiation has been found to correspond with an increase of asymmetry. Such increase, however, is very slight compared with the increase in penetrating power of the exciting radiation.

In conclusion, I wish to express my great indebtedness to Prof. Barkla for the interest he has shown and the advice he has given during the course of this investigation.

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